# IMPROVEMENT OF PILE CAPACITY IN MARINE SOIL BY ELECTROKINETICS

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CERTIFICATION OF APPROVAL

**Improvement of Pile Capacity in Marine Soil by Electrokinetics**

by

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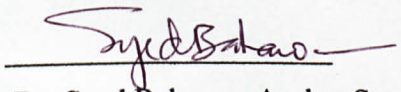
Approved by,



(Dr. Syed Baharom Azahar Syed Osman)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2009

## CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AHMAD AZIMI BIN KAMALUDDIN

# ABSTRACT

This report serves as the progress report for the Final Year Project 2 entitled "Impovement of Pile Capacity in Marine Soil by Electrokinetics". A brief introduction regarding the stabilization of soil, electrokinetics and electrochemical are written. The methods of investigation involved for the project are soil properties investigation (index and engineering properties), electrokinetic treatments, pull-out test, as well as several main properties, i.e. the moisture content and pH. Steel cylinder is used as the pile in this study. The treatment is done in a 76 x 41 x30 cm treatment box that has two equivalent size compartments to run two treatments simultaneously. The box is reinforced with L-shaped aluminium bars so that it will be able to sustain the weights of the soil and surcharge applied. The experiment is divided into two main phases: consolidation phase and treatment phase. In the consolidation phase, the steel cylinder is embedded into the soil and weights are placed above the soil to consolidate the soil. This phase serves to simulate the consolidated seabed in the marine condition. In treatment phase, the weights are taken off and DC electric current is applied on the electrodes placed within and without the perimeter of the steel cylinder. The treatment phase takes 7 days, and the treatment phase takes 14 days. Two treatments are conducted. One treatment is with single polarity, and the other with polarity reversal. In the treatment with polarity reversal, the first 7 days of the treatment phase will be done with electrode configuration similar with the first treatment, and the polarity is reversed on the eighth day for the second 7 days. Once the 21 days are up, the pullout test, the main parameter studied and analyzed in this study, is conducted using Universal Testing Machine 5kN to measure the pullout capacity of the pile. The result of the pull-out test and the vane shear test shows increase in soil strength.

# ACKNOWLEDGEMENT

First and foremost, the author desires to express his warmest gratitude to his Final Year Project supervisor, Dr Syed Baharom Azahar Syed Osman, for having been very helpful and encouraging. From the start of the project, he has guided the author from the most minuscule detail to the biggest of hurdles. He has taught how to conduct a proper research, starting from the inception, through the practical hands-on, on to the presentation of findings. His emphasis on the utter understanding of the subject, theoretically and practically, has set the author to embark on comprehensive study and preparation for the undertaking. He has instilled and developed in the author, the sense of teamwork, good communication skills and project management.

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Last but not least, laboratory technicians in Mechanical Engineering Department, Administrative personnel of Civil Engineering Department, UTP's transportation personnel, and the helpful staff of Jabatan Mineral dan Geosains Malaysia in Ipoh.

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# CHAPTER 1
# INTRODUCTION

## 1.1 BACKGROUND OF STUDY

Urbanization, industrial development and oil exploration, due to logistics, most often take place in the coastal regions. Hence soft clays are invariably encountered in geotechnical engineering practice. Stress, time and environment play a dominant role in the formation of soft clay. They are mutually exclusive processes, with the principle of superposition of their effects not being tenable. The shear stress-strain behavior of in-situ soft clays, although seemingly akin to that of stress-strain-pore pressure or volumetric strains are considered in totality.

The design and construction of infrastructure facilities in the soft soil of coastal regions made necessary by extensive urbanization and industrialization entail detailed assessment of their engineering properties and their adequacy to meet the practical needs. This is made more crucial with the growing scarcity in available land for use as proved by the increasing number of constructions spreading out over both land and sea, construction in ever-deeper below ground, as well as higher buildings. Not only that, is has become more necessary to improve ground condition below or surrounding existing structures that undergo distress to restore their stability.

Soil stabilization is very crucial to the stability of the structures lying on top of and underneath it. Unstable soil, whether by settlement or expansion, has caused severe damages to structures in the past. This is applies also for structures on under the marine conditions. Poor ground conditions have also proved to render construction costs rising. Thus, it is economically feasible to improve the engineering properties of the ground first before commencing the structure construction.

The principles behind the ground improvement are mainly the reduction of pore water pressure, reduction of volume of voids in the soil, or by the addition of stronger materials. Some of the widely applied soil stabilization methods are vacuum consolidation, perforated vertical drain (PVD), compaction, grouting, and laying geotextiles.

The objectives of ground improvement are:

- Reduce settlement of structures
- Improve shear strength and bearing capacity of shallow foundations
- Increase factor of safety against possible slope failure of embankments and dams.
- Reduce shrinkage and swelling of soils.

According to Hoeg (1986), seafloor instability and slope movements are reported from several areas, for instance the Gulf of Mexico and offshore Alaska and Norway. Mainly since these events, ocean floor instability has been studied in a much broader sense. Several of the main types of oil platform foundations are the Hutton tension-leg platform, Magnus steel-template-jacket platform and Guyed tower. The foundations of these platforms undergo both tension and compression forces when ocean waves exert lateral forces on the platforms. Thus, it is important to increase the tension (pull-out) and the compressive capacity of the piles in the seabed.

## 1.2 PROBLEM STATEMENT

The problem related to soil instability could cause severe economical and physical damages. This problem is most apparent in areas predominantly consisting of clayey materials. Typically, marine clays show shear strengths ranging from 35 kPa to 14 kPa. Furthermore, marine clay is highly impermeable and cohesive. Its behavior is mainly determined by their particle shape, mineralogical composition and water content.

These qualities present several problems:

- Short-term bearing strength
- Weak to penetration due to low bearing and side shear strength. Plus, short-term cohesion is often lower than long-term, thus any dynamic forces acting on the clay strata usually result in reduction of shear strength.
- Scour that occurs when strong bottom currents exist. Scour pockets in clays do not continuously refill as they do in sand. Thus, severe scour in the vicinity of a structure may be proceeded by a process of undermining and collapse.

## 1.3 OBJECTIVES AND SCOPE OF STUDY

The objectives of the study are:

- To study the effects of electrokinetics treatment on the properties of marine soil, focusing in the strength parameters.
- To study the pullout capacity of the soil after treatment.

The scope of this study includes:

- Literature review on the works by previous researchers such as regarding electrokinetics method on different soil condition, improvement of load-carrying capacity of foundations, the marine clay properties, etc.
- Determination of soil properties of the marine clay
- Acquisition of marine soil sample, preparation of the soil, and the consolidation as well as the treatment of the soil.
- Determination of shear strength, pH and moisture content after the treatment of the soil.
- Pullout test on the treated soil.
- Analysis of the data and presentation of the findings.

Preliminary works are conducted in the Geotechnical laboratories. However, several sessions of experiments are conducted in-situ. The length of each experiment is approximately three weeks (7 days of consolidation phase and 14 days of treatment phase).

For the purpose of this report, the terms electrokinetics and electrochemical are used alternately to describe the same process. Explanation to this will be provided in the next section.

# CHAPTER 2
# LITERATURE REVIEW AND THEORY

## 2.1 CHARACTERISTICS OF SOFT CLAY

Firstly, the inherent characteristics of soft clay is to be presented as soft ground comprises of deposits having potential for high compressibility and possessing low strength. The characteristics are the compressibility, shear strength and permeability.

According to Nagaraj et al. (2001), a typical compression path of soft soil is of inverse S-shape. The three zones of the compression path are as shown in Figure 1. In level 1, the compression is negligible. Beyond Zone 1, the compression is high and in zone , it changes its curvature.The compression index $C_c$ for the entire stress range can be regarded as being of the same magnitude. On the contrary, as the yield stress level increases the stress range over which negligible compression is experienced would also increase. This allows higher stress level to which soft clays can be loaded without the risk of culminating in appreciable settlement. Beyond the first zone, there is sudden compression of the clay, with the compression index far greater than that for the remolded state.

The consistency of clay can be described by its unconfined compressive strength, $q_u$ or by its undrained shear strength Su. Clay is regarded as very soft if its unconfined compressive strength is less than 25 kPa and as soft when the strength is in the range of 25 to 50 kPa (Terzaghi & Peck 1967).

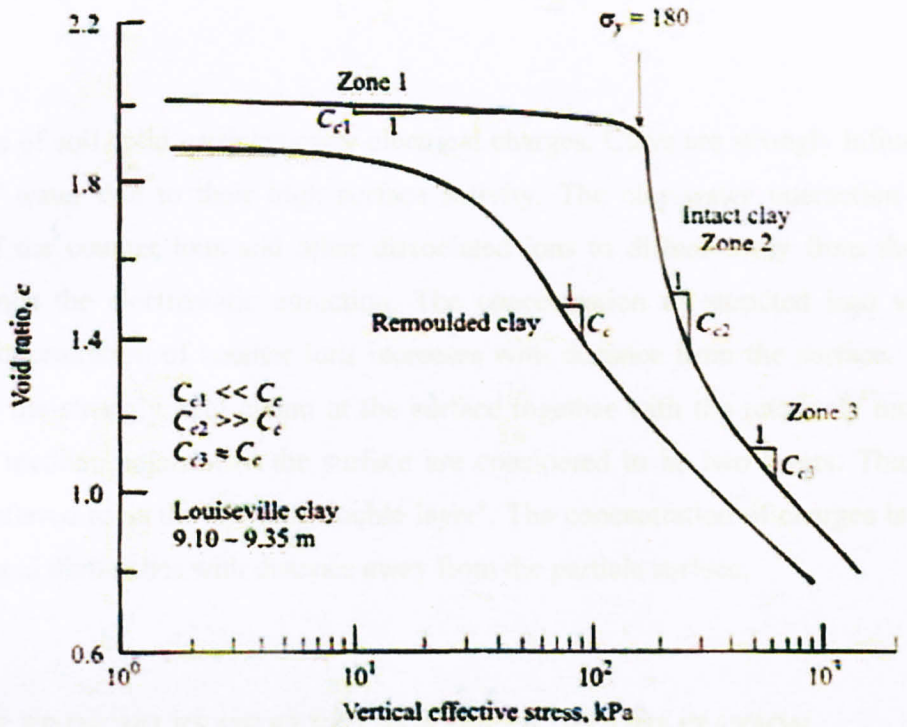



**Figure 1: Typical compression path of soft sensitive clay**

According to Nagaraj, clay may be soft from shear strength point of view, but the compressibility could be low if the liquid limit contents are relatively low. On the other hand, if the liquidity index of a soft clay is greater than unity, with water contents higher than the liquid limit, the undrained strength of such clays can be in the strength range of 25-50 kPa due to cementation. This is due to the fact that for water contents corresponding to their liquid limit the undrained shear strength is only in the range of 1.5 to 2.5 kPa.

The analysis of engineering problems requires two types of permeability values, which are the magnitude and anisotropy of 'k' at in-situ void ratio and its variation as clays are compressed. Mesri & Tavenas (1983) contend that for the range of stress normally encountered, the linear relationship between the void ratio and logarithm of permeability is tenable. The merit of such a linear relationship is to define permeability in terms of a permeability index, defined as the slope of $e$-log $k$ path, and to relate it to the change in void ratio.

$$e = C_x \Delta \log k$$

where $C_k$ is the permeability index similar to the compression index $C_c$ and dependant on void ratio.

The surfaces of soil solid particles carry electrical charges. Clays are strongly influenced by the presence of water due to their high surface activity. The clay-water interaction results in a tendency of the counter ions and other dissociated ions to diffuse away from the surface, to counterbalance the electrostatic attraction. The concentration of attracted ions will diminish while the concentration of counter ions increases with distance from the surface. The charged surface and the strongly held cation at the surface together with the relatively mobile counter ions in the medium adjacent to the surface are considered to be two layers. Thus, the whole system is referred to as the 'Diffuse double layer'. The concentration of charges is greater near the surface and diminishes with distance away from the particle surface.

## 2.2 THE PRINCIPLES OF ELECTROKINETIC STABILIZATION

A number of studies have been done by previous researchers. According to Kassim et al. (2003), the first application of electrokinetic to soil was done by Casagrande (1951) when he observed a reduction of moisture content in the wet clayey soil he tested on. Electrokinetic stabilization of soil is closely linked to electroosmosis. According to J. E. Barker et al. (2004), the term electroosmosis is "a method of reducing the water content of the soil *in situ* and thereby increasing the shear strength".

Electrokinetics embodies three different processes that were explained by Kassim as following:

- Electrophoresis: the migration of charged colloids, not small ions, in solid-liquid mixture under electric potential gradient, where discrete particles are transported through water. If a direct current (DC) is applied to clay-water systems, negatively charged clay particles will migrate towards the anode. In a compact system of porous plug, electrophoresis is of less importance due to restrained solid phase.
- Electromigration: the movement of charged ions towards the oppositely charged electrodes relative to solution. In a dilute system or a porous medium with moderately

concentrated aqueous solution of electrolytes, electromigration of ions is the major cause of current conduction. With regard to contaminated soils, electromigration is the primary mechanism of electroremediation when the contaminants are ionic of surface charged.

- Electroosmosis: involves water transport through continuous soil particle network, where the movement is primarily generated in the diffuse double layer or soil moisture film. The principle mechanism in electroosmosis is the migrating ions, where the cations migrate to the cathode and the anions move towards the anode (Gray and Mitchell, 1967). Accordingly, when an electric field (DC) is applied to clay-water system, the surface or particle is fixed, whereas the mobile diffuse layer moves carrying solution with it.

Furthermore, due to the nature of clay formation, which usually results in significantly negative charged clay particles, the predominant ions within the pore fluid are incidentally cationic. Thus, clayey soil has significantly greater number of cations than that of anions. This results in the general flow of water in the direction of the cathode (Mitchell, 1991).

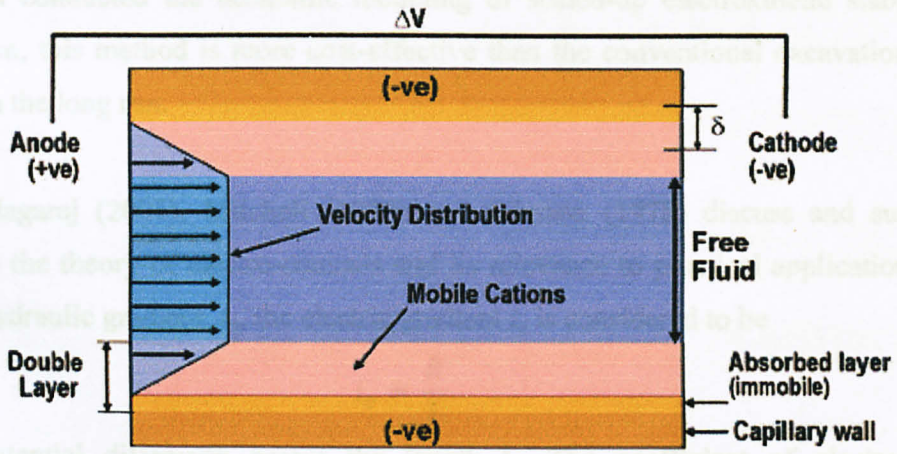



**Figure 2: Helmholtz-Smoluchowski model for electroosmosis flow (after Mitchell 1993)**

Based on Helmholtz-Smoluchowski theory, one of the most widely used theory for electroosmosis (Figure 2), in elaborating on the concept of diffuse double layer system, the inner wall of the double layer which is relatively thin compared to the outer wall, consists of

negatively charged ions firmly attached to the wall, outside of which consists of mobile positive ions.

When a direct current is applied, the mobile positive cations will be attracted towards the cathode, dragging with them the free water molecules causing general movement of water from anode to cathode.

By the migration of water ions from anode to cathode, the porewater pressure in the general area of the soil will be reduced and thus will improve the shear strength of the soil. The migrated water can be isolated and discarded by physical means, such as drainage.

According to Shang (1997), the factors affecting the performance of electrokinetic stabilization are internal and external in nature. The intrinsic factors include the grain size and mineral type, salinity, pH, hydraulic permeability, current density, and electrode material and design. The parameters have been studied by Hamed et al. (1997), Schultz (1997), and many more. Schultz (1997) has even conducted the economic modeling of scaled-up electrokinetic stabilization. According to him, this method is more cost-effective than the conventional excavation and ex situ treatment, in the long run.

According to Nagaraj (2001), Mitchell (1970) and Johnson (1978) discuss and summarize developments in the theory of electro-osmosis and its relevance to practical applications. In an analogy to the hydraulic gradient, $i_h$, the electric gradient $i_e$ is considered to be

$$i_e = \frac{E}{L}$$

Where E is potential difference across the length L. The coefficient of electro-osmotic permeability, $k_e$, as a function of the drainage parameters, is:

$$k_e = \left(\frac{Q}{A}\right)\left(\frac{1}{i_e}\right) = \left(\frac{cm^3}{\sec \times cm^2}\right)\left(\frac{cm}{volt}\right) = \left(\frac{cm^2}{\sec \times volt}\right)$$

Because the hydraulic coefficient of permeability, $k_h$, is measured in cm/sec it is more convenient to define $k_e$ also in cm/sec for a constant potential gradient of one volt/cm.

Electro-osmotic permeability is independent of the soil pore size as $k_e$ is nearly of the same magnitude for sands, silts and clays, provided that the electro-osmotic potential is about the same for most of the mineral matter in the soil. For practical purposes, for most saturated soils a coefficient of electro-osmotic permeability of 5 x $10^{-5}$ cm/sec per volt/cm can be used for dewatering and consolidating clays.

For assessment of relative efficacy of electro-osmotic dewatering, the hydraulic conductivity of the soft clay must be estimated. In Table 1, the data of $k_e$ values of a number of soils along with the efficiency factor, F, due to electrokinetic is shown. From the table, electrokinetic is not suitable for fine sands and silts.

**Table 1: Efficiency factors due to electrokinetic drainage**

| Soil Type | Water Content | $K_e$ ($10^{-5}$ cm/sec) cm/volt | $F = k_e/k_h$ |
|---|---|---|---|
| **London clay** | 52.3 | 5.8 | 5800 |
| **Blue Boston clay** | 50.8 | 5.1 | 5100 |
| **Commercial kaolin** | 67.7 | 5.7 | 570 |
| **Clayey loam** | 31.7 | 5.0 | 50 |
| **Rock flour** | 27.2 | 4.5 | 450 |
| **Ca-bentonite** | 170 | 2.0 | 2000 |
| **Na-bentonite** | 2000 | 12.0 | 12000 |
| **Mica powder** | 49.7 | 6.9 | 1.25 |
| **Fine sand** | 26.0 | 4.1 | 0.4 |
| **Quartz powder** | 23.5 | 4.3 | 0.4 |

Furthermore, Nagaraj (2001) elaborated that another distinct characteristics of electrokinetic drainage is by placing the cathode and anode relatively to each other, the direction of the flow can be controlled.

## 2.3 ELECTROCHEMICAL STABILIZATION OF SOIL

The experimental setup for electrochemical stabilization is similar to that of electro-osmosis, but with an addition of electrolytes at the anode, cathode, or throughout the soil sample. It has been discovered that this method has greatly facilitates the transport of desired ions through the soil, thus enhancing the stabilization process of the soil.

Like the traditional chemical stabilization, electrochemical stabilization improves the soil properties through modification and stabilization reactions, with the additional advantage in transporting 'desired ion' through the soil enhancing the ability to strengthen the soil modification and especially stabilization through cementing process.

Electrochemical stabilization is conducted by injecting predetermined electrolytes at the anodes and cathodes and inducing direct current electrical field throughout the soil.

According to Adamson et al. (1965), the degree of soil stabilization and course of the process are affected by clay content, types of clay present, the concentration of the salt in the soil, increase of soil temperature during the treatment, and the types of chemicals added into the soil. The mechanism of movement of ions and water is explainable by electrokinetics principles, whereas the mechanism of stabilization is explainable of the traditional chemical stabilization (Barker et al., 2004).

As explained by Syed (2007), the main mechanisms in electrochemical stabilization are modification, cementation, and precipitation. These are briefly explained as following:

- Modification: Studies of clay mineralogy has shown that surface forces are the predominant factor in influencing the properties of clay. From the isomorphous substitution of aluminium or silicon atoms by the lower-valency atoms, the surface is negatively charged, which provides attraction to the dipolar water molecules. Thus, diffuse double layer is formed, which layer thickness is controlled by the concentration of cations in the vicinity and the surface charge of the clay particles. When high concentration of high valency cations such as calcium and aluminium are high in

concentration, they replace lower-valency ions, resulting in thinner layer of the double diffuse layer. This, in return, allows closer contact between the clay platelets, and promoting edge-to-edge attraction, or more commonly known as flocculation (Figure 3). Hence, the change in the workability of the soil, permeability, plasticity, and swell properties.

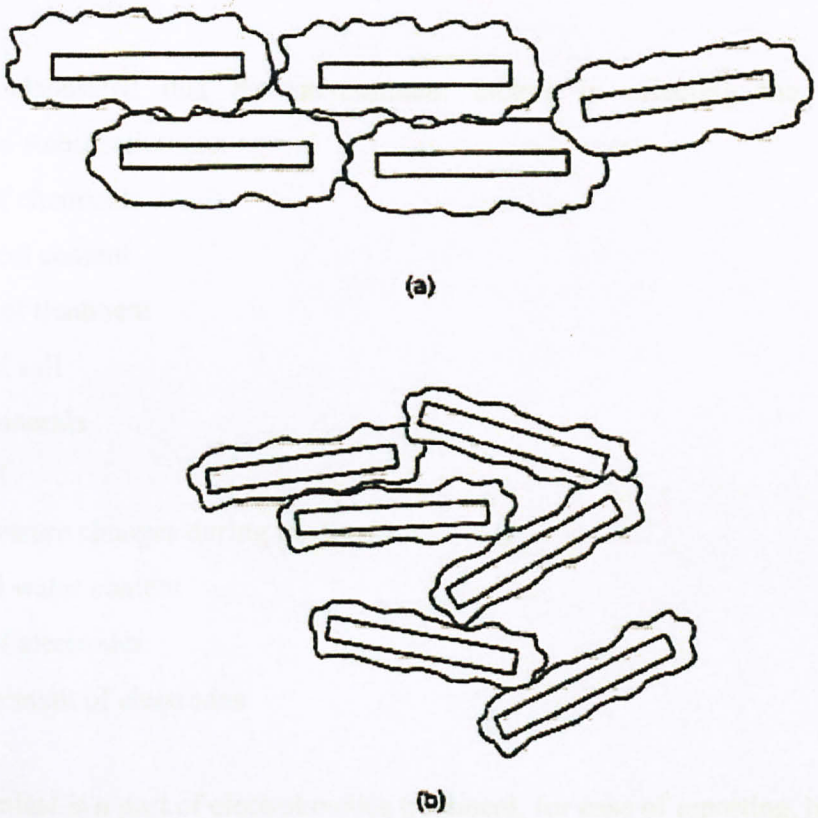



**Figure 3: Flocculation of clay particles (after Little, 1987): (a) parallel arrangement of clay particles with hydrated water layers; (b) edge-to-edge attraction induced by thin layer, which allows attractive forces to dominate**

- Cementation: This process occurs in high pH condition, which is usually more than 10. The alkaline environment catalyses the dissolving of $SiO_2$ and $Al_2O_3$ from the clay particles and they will react with $Ca^{2+}$ ions from stabilizing agents. Then cementitious materials are formed under pozzolanic reaction. The materials are calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH).

$$Ca^{2+} + 2(OH)^{-} + SiO_2 \rightarrow CSH$$

$$Ca^{2+} + 2(OH)^{-} + Al_2O_3 \rightarrow CAH$$

- Precipitation: occurs when ion from one solution comes in contact with that from another to form crystals of insoluble salts. This process is the main strengthening mechanism in certain electrochemical stabilization, especially in pH condition greater than 7.

Syed further elaborated that the predominant factors in affecting the effectiveness of electrochemical stabilization are:

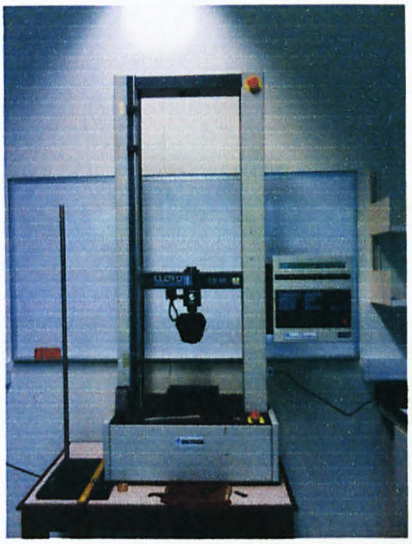
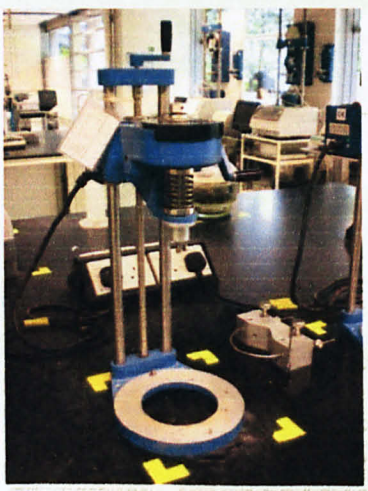
- Type of chemicals
- Chemical content
- Period of treatment
- Type of soil
- Clay minerals
- Soil pH
- Temperature changes during treatment
- Natural water content
- Type of electrodes
- Arrangement of electrodes

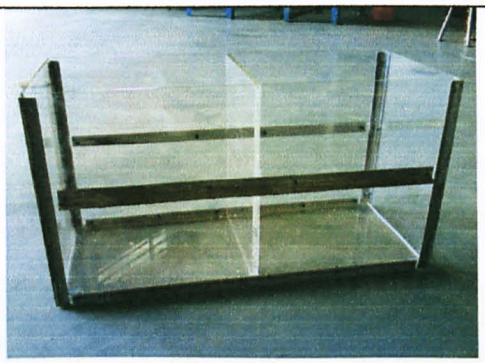
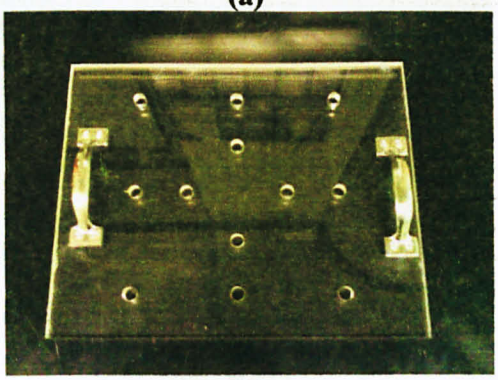
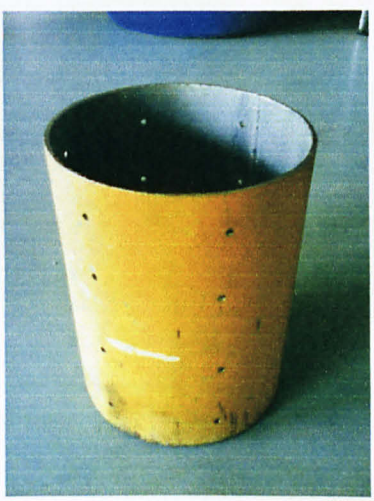
As electrochemical is a part of electrokinetics treatment, for ease of reporting, both terms will be used alternately to describe the same process.

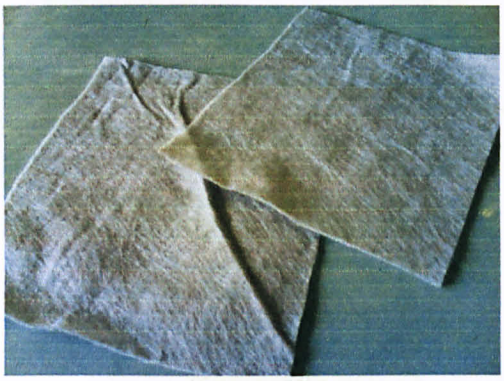
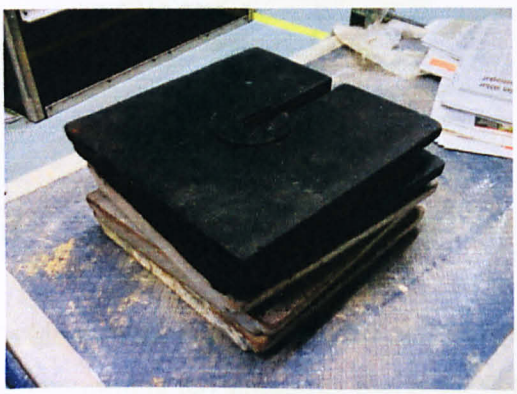
# CHAPTER 3
# METHODOLOGY

## 3.1 APPARATUS AND MATERIALS

| Apparatus / Materials | Functions |
|---|---|
| Drying Oven | To oven-dry the marine clay. Reducing the water content to as close as 0%. This will enable the soil to be wetted to required moisture content. |
| Los Angeles Abrasion Machine  **Figure 4** | To grind and crush the oven dried marine clay into small particles. |
| Sieving machine | To obtain soil particles that pass 2 mm sieve filter. |
| Mixing machine  **Figure 5** | To thoroughly water-mix the oven-dried and sieved marine clay |

| | |
|---|---|
| Universal testing machine 5 kN<br>  <br>**Figure 6** | To conduct the pullout test after treatment of soil. |
| Vane shear test machine<br>  <br>**Figure 7** | To conduct the shear test on the treated soil |
| Treatment Box complete with cover | To provide a platform where the treatment of the marine clay can be observed in controlled conditions. The box has two compartments with individual dimensions of 37 cm long, 30 cm wide and 40 cm of height. The material used for the construction of the box is 5 mm |

| | |
|---|---|
|  <br>(a)<br>  <br>(b)<br>**Figure 8** | thick Perspex, due to its easy handling, ease of acquisition and its impact resistant properties. The treatment box is reinforced with aluminium L-shapes to prevent from failure of box.<br><br>The cover of the box is made of similar material, with two handles at each end for ease of handling. The cover is drilled for holes to cater to the protruding electrodes for the treatment of the marine soil sample. |
| Steel cylinder<br>  <br>**Figure 9** | Simulates the pile foundation.<br>The cylinder is perforated to allow lateral contact of soil within and without the cylinder. This will provide channels for the migration of water and ions.<br>The dimensions are 22 cm of height and 15.24 cm (6 inches) of diameter. |
| Electrodes | Placed vertically to allow electric charge to flow.<br>Consists of cathode (negative electrode) and |

| | |
|---|---|
| | anode (positive electrode).<br>The electrodes used for the treatment are made of steel.<br>The length of each electrode is 35 cm. |
| Geotextile layer<br>  <br>**Figure 10** | To provide drainage for the water to surface upwards during the consolidation phase. |
| Salt water | To simulate the salinity of seawater |
| Weights<br>  <br>**Figure 11** | To stimulate consolidation |
| Multimeter and DC power supply | Supplying DC current with determinable amount to the electrodes |

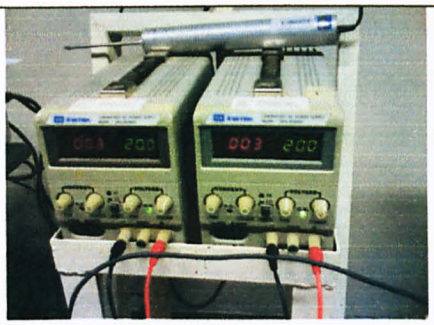


**Figure 12 : DC power supply**

Current logger

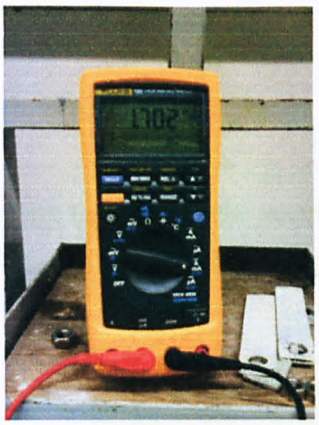


**Figure 13**

Recording the currents (ampere) throughout the treatment of the marine clay

## 3.2 TESTS ON SOIL PROPERTIES

To identify the properties of the soil sample, attention will be given to conducting basic soil tests in determining the suitability and properties of the marine clay sample. The tests to be conducted are:

1. Oedometer Test : To determine consolidation characteristics of solid of low permeability
2. Vane Shear Test: To determine shear strength of a sample of soft to firm cohesive soil.
3. Determination of Moisture Content (Oven-drying method)
4. Particle Density or Specific Gravity
5. Determination of Particle Size Distribution

6. Determination of Plastic Limit
7. Cone Penetration : To determine the liquid limit
8. Permeability Test (Constant Head Method)
9. Determination of pH
10. Determination of conductivity of soil

These tests will be conducted mostly in Civil Engineering Department with the help of the lab technicians and lab manuals. The procedures are outlined in the provided lab manuals.

## 3.3 SOIL PREPARATION

In preparing the soil for the consolidation and treatment phases, the following steps are taken:

1. Marine soil is obtained from the suitable location.

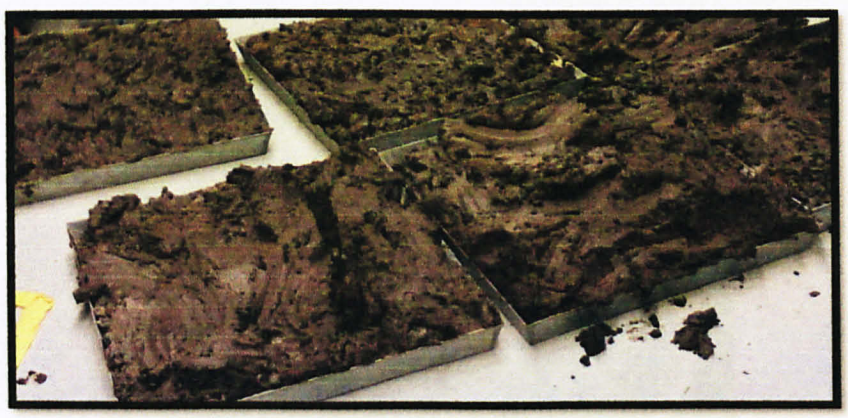


**Figure 14: The marine clay acquired**

2. The soil is oven-dried to ensure no water content is remaining.
3. The soil is crushed to obtain fine particles (Figure 15).

**Figure 15: Crashing the soil using the Los Angeles Abrasion Machine**

4. The soil is sieved through 2 mm sieving filter and the passing soil is taken for the treatment.
5. The soil is mixed with saline water at 55% of its weight and kept overnight (Figure 16).

**Figure 16:** The sieved soil mixed with saline water

6. The soil is placed inside the treatment box and ready for the consolidation.

## 3.4 CONSOLIDATION OF SOIL

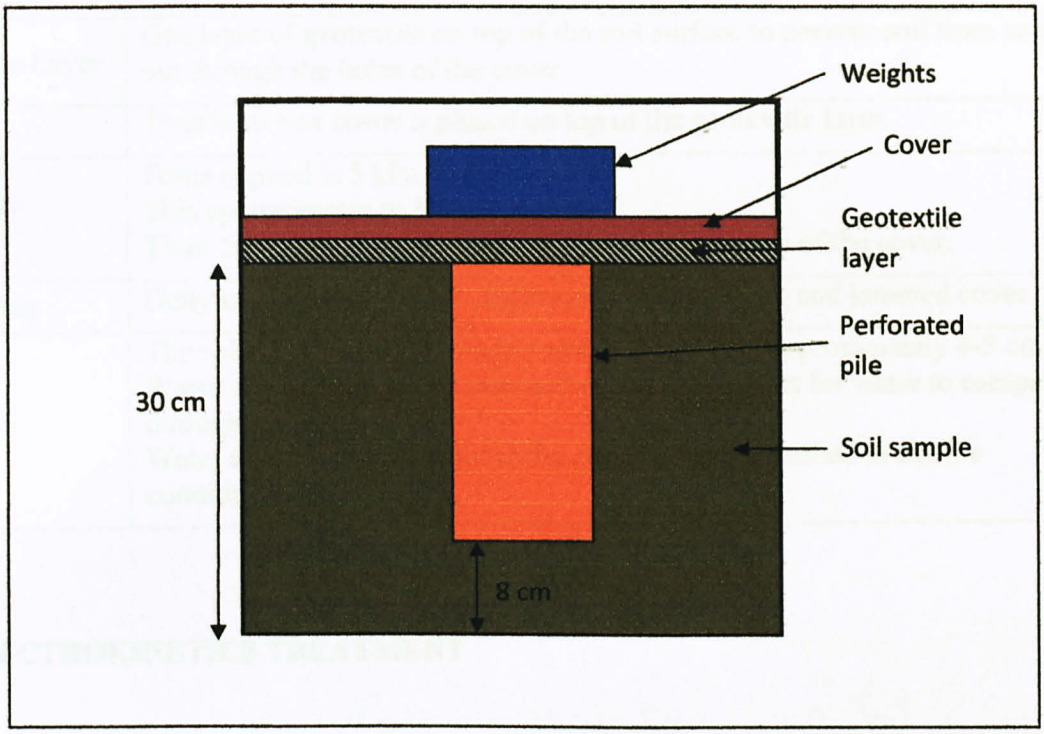



**Figure 17: Front view of one compartment of the treatment box during the consolidation phase**

| | |
|---|---|
| Objective | To simulate the consolidated soil in marine condition |
| Apparatus and materials involved | Treatment box complete with covers<br>Perforated steel cylinder<br>Soil sample<br>Salt water<br>Geotextile<br>Weights |
| Duration | 7 Days |
| Soil Sample | Soil pass 2mm sieve.<br>55% water content.<br>Filled to 30 cm of height of treatment box.<br>Soil sample is scooped into the treatment box by layers with rodding at each layer to avoid voids forming up in the sample. |
| Salt Water | Salt water simulates the salinity of seawater.<br>Salinity is 3.5%. This means 35 g of salt in every 1 kg of distilled water. |
| Perforated Steel | Cylinder length is 22cm. |

| | |
|---|---|
| Cylinder | The cylinder is pushed into the soil so that the top of the cylinder is leveled with the surface of the soil and it is hanging at 8 cm above the bottom of the box. |
| Geotextile Layer | One layer of geotextile on top of the soil surface to prevent soil from seeping out through the holes of the cover |
| Cover | Treatment box cover is placed on top of the geotextile layer. |
| Surcharge / Weights | Force applied is 5 kPa.<br>This approximates to 50 kg.<br>Thus, 5 nos. of 10 kg weights will be applied on top of the cover. |
| Monitoring | Daily inspection to ensure settlement without tilting and jammed cover |
| Inference | The soil sample is consolidated and will settle for approximately 4-5 cm.<br>Water will surface since there will not be any outlets for water to escape through.<br>Water at the surface simulates the seawater above seabed in marine condition. |

## 3.5 ELECTROKINETICS TREATMENT

| | |
|---|---|
| Objective | To apply DC electric current to stabilize the soil sample<br>To increase the pullout capacity of the soil |
| Apparatus and materials involved | Treatment box complete with covers<br>Perforated steel cylinder<br>Soil sample<br>Salt water<br>Geotextile<br>Weights<br>Electrodes<br>Multimeter<br>DC power supply<br>Current logger |
| Duration | 14 Days (2 weeks) |
| Surcharge | The weights are unloaded off of the soil sample. |
| Salt water | Salt water simulates the salinity of seawater.<br>Salinity is 3.5%. This means 35 g of salt in every 1 kg of distilled water. |
| Electrodes | Electrodes are embedded into the soil.<br>Front view is shown in Figure 18. |

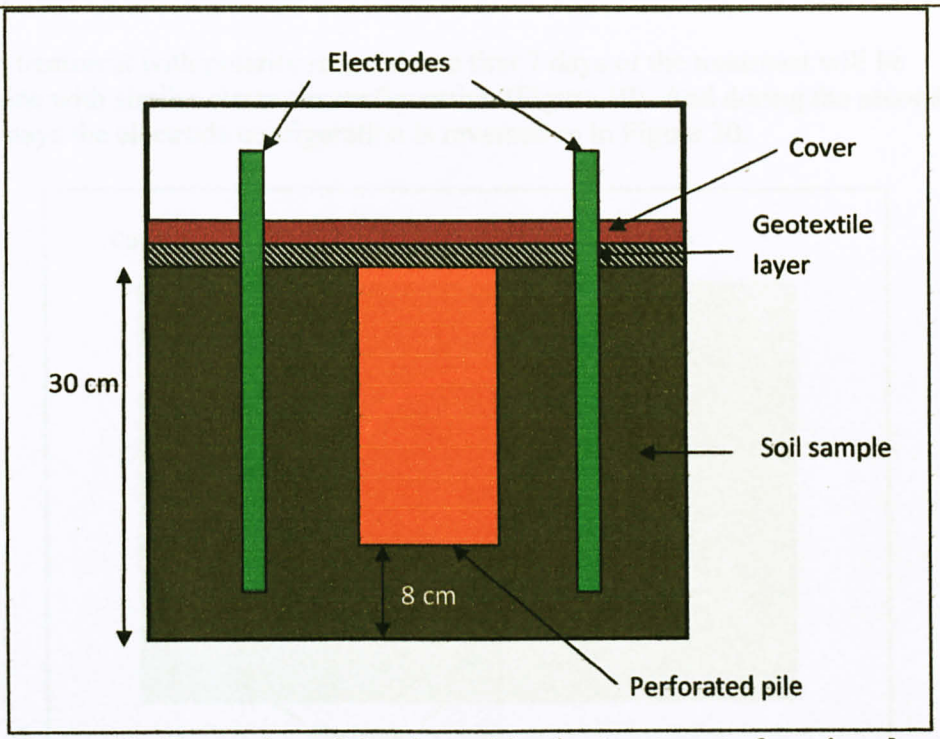



**Figure 18 : Front view of the electrokinetics treatment of marine clay**

The position of the electrodes in plan view is shown in Figures 19 and 20.

For treatment with single polarity, 4 cathodes are placed inside the perimeter of the cylinder and 8 anodes are placed outside of the cylinder perimeter.

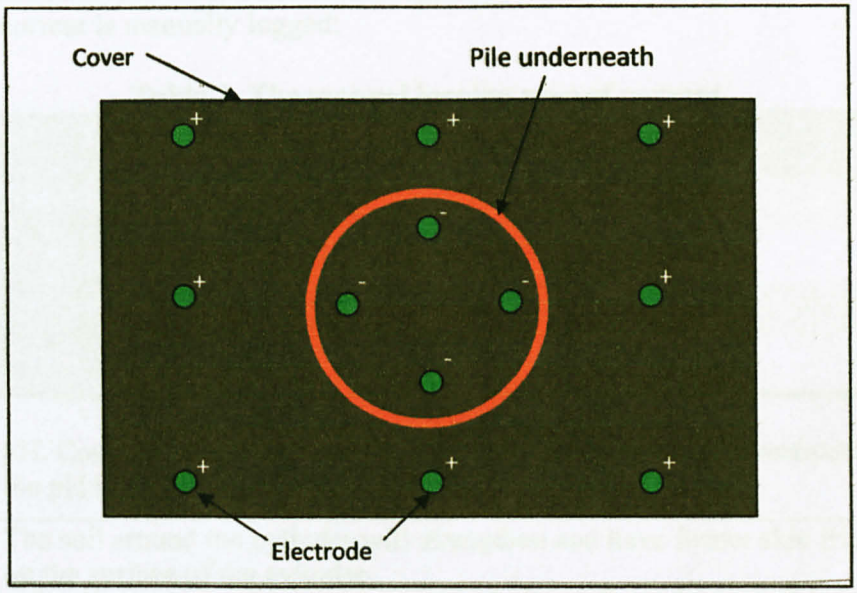



**Figure 19 : Plan view of the position of the electrodes for treatment with single polarity**

In treatment with polarity reversal, the first 7 days of the treatment will be done with similar electrode configuration (Figure 19). And during the second 7 days the electrode configuration is reversed as in Figure 20.

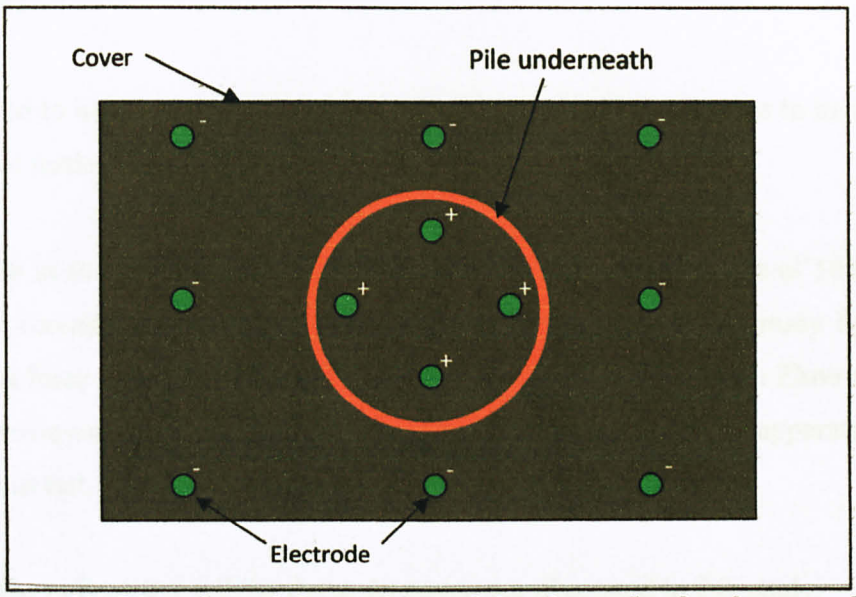



**Figure 20: Plan view of the position of the electrodes for the second 7 days of treatment with polarity reversal**

| | |
|---|---|
| Power supply | The electric current used is direct current (DC)<br>Voltage: 10 V |
| Monitoring | 1. Electric current. Automatically logged by the current logger. The initial current is manually logged:<br><br>**Table 2: The manual logging plan of current**<br><br>2. pH. Conducted once to determine the initial pH. After each treatment, the pH is determined again. |
| Inference | 1. The soil around the cylinder will strengthen and have firmer skin friction on the surface of the cylinder.<br>2. A soil layer will be firmly attached to the steel cylinder and electrodes. |

| Interval | Repetition | Total Time |
|---|---|---|
| 5 seconds | 24 | 2 minutes |
| 15 seconds | 20 | 5 minutes |
| 30 seconds | 16 | 8 minutes |
| 5 minutes | 12 | 1 hour |

| | |
|---|---|
| | 3. The average shear strength will increase significantly. |

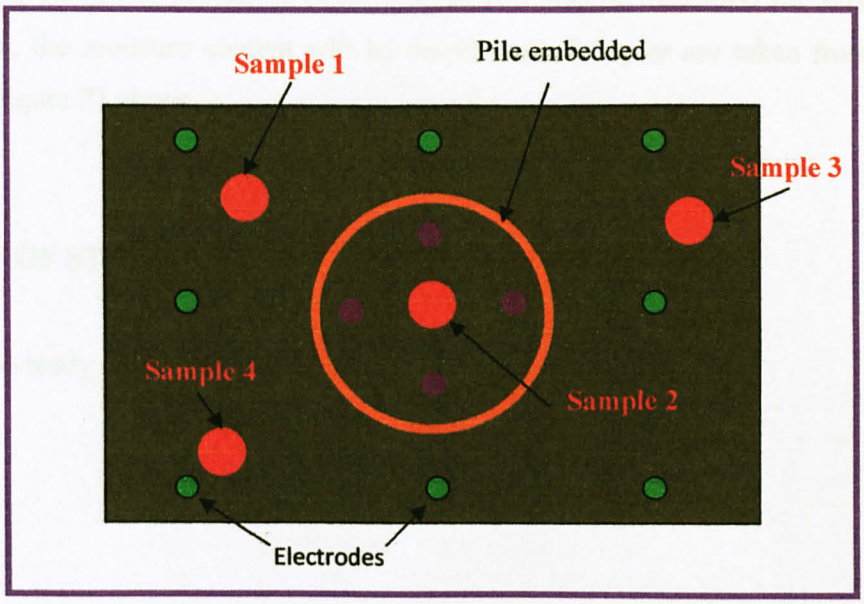
## 3.6 PULL-OUT TEST

Pull-out test is widely used to measure the pull-out capacity of the soil. The apparatus to be used for the test is the universal testing machine 5000 N.

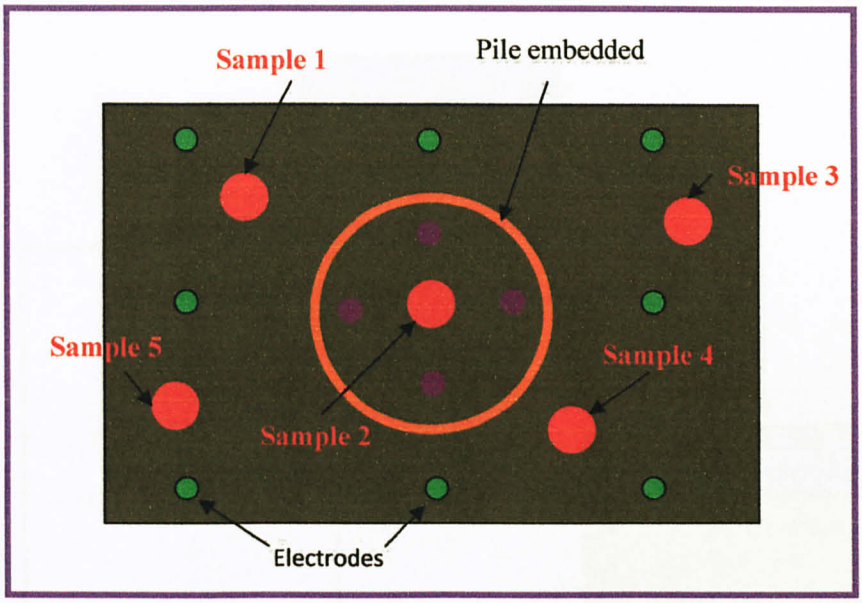
The apparatus is available in the Mechanical Engineering Building laboratory and is of 5000 N capacity (Figure 6). The constant speed of pull-out is set to 50 mm/ min. In the study by N. Gurung et al., the pull-out force was in the range of 0-30 kN and in that of Wan-Huan Zhou et al., the range is 0-35 kN. However, in the case of marine clay, this capacity of this apparatus is suitable to conduct pull-out test.

The data available from the pullout test will be the main parameter discussed in this study.

## 3.7 TESTS ON SHEAR STRENGTH, pH AND MOISTURE CONTENT




(a)




(b)

**Figure 21: The electrode configuration and locations of sampling (a) Treatment with single polarity (b) Treatment with polarity reversal**

After conducting the electrokinetic experiments, the soil will undergo shear strength tests using vane shear test apparatus and possibly direct shear box test.

Apart from that, the pH of the soil in several areas will also be measured for data and analysis purposes. Then, the moisture content will be determined. Samples are taken from locations as illustrated by Figure 21 above.

## 3.8 FLOW OF STUDY

The flow of this study will be as following:

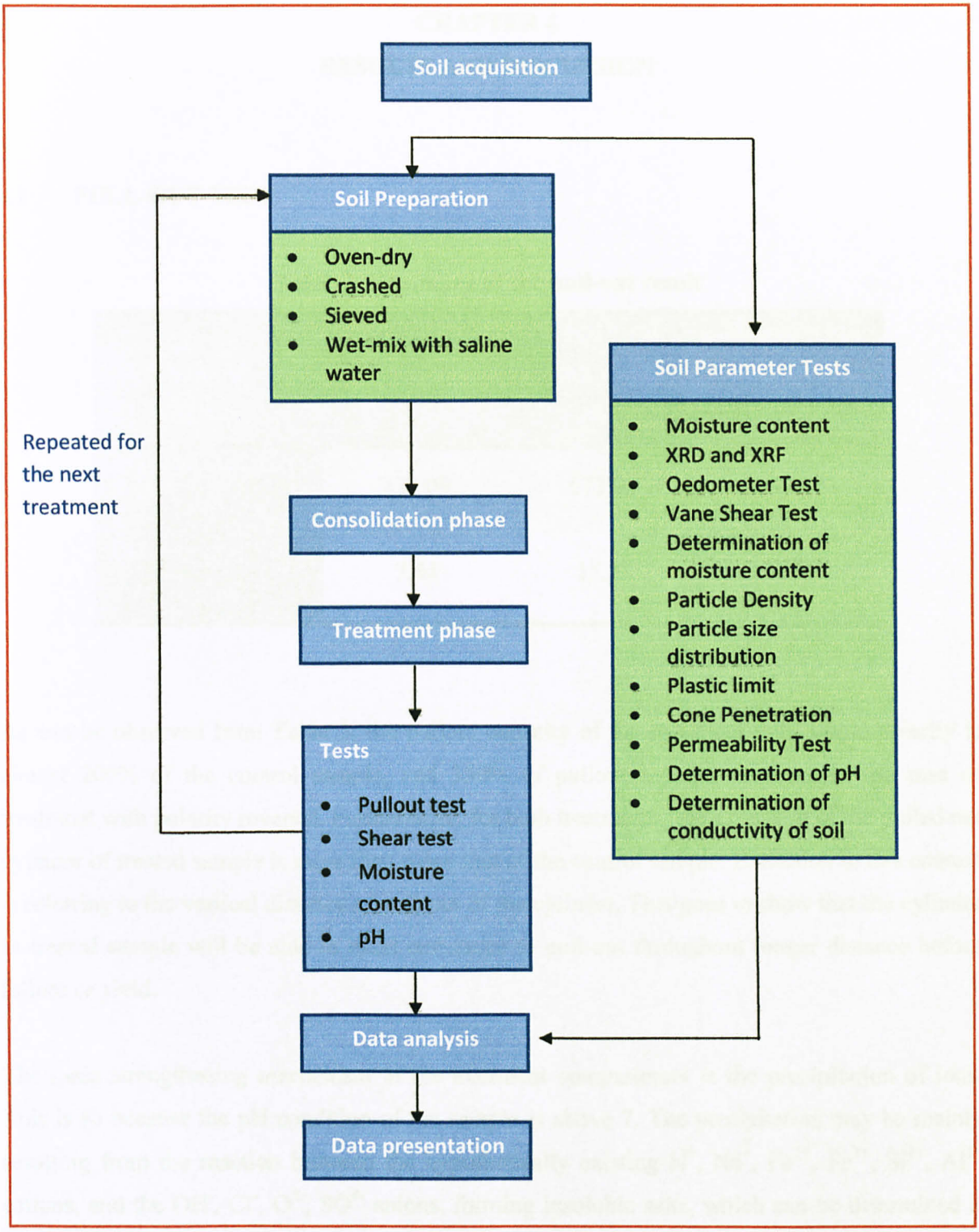



**Figure 22: Flow of study**

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 PULL-OUT TEST

**Table 3: Summary of the pull-out result**

| Sample | Control | Treatment with single polarity | Treatment with polarity reversal |
|---|---|---|---|
| Pullout Capacity (N) | 223.09 | 673.33 | 990.86 |
| Deflection at Yield (mm) | 7.64 | 15.36 | 17.91 |

As can be observed from Table 3, the pullout capacity of the treatment with single polarity is almost 200% of the control sample, and 350% of pullout capacity increase in the case of treatment with polarity reversal. Furthermore, for both treatments, the extension of the pulled out cylinder of treated sample is more than twice that of the control sample. Extension in this context is referring to the vertical distance of pull-out of the cylinder. This goes to show that the cylinder in treated sample will be able to exert resistance to pull-out throughout longer distance before failure or yield.

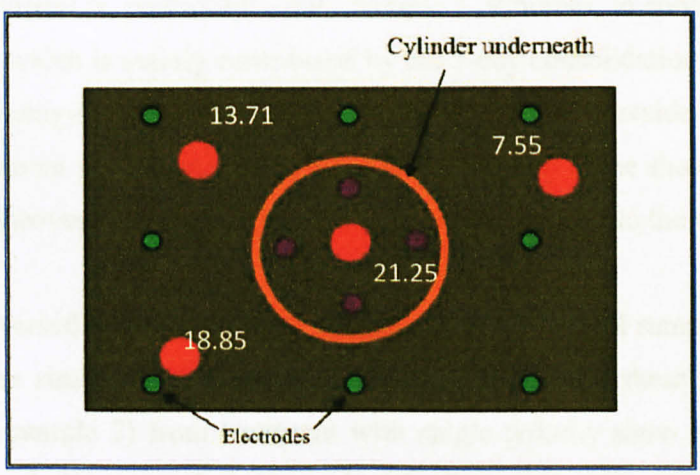
The main strengthening mechanism in the treatment compartment is the precipitation of ions. This is so because the pH condition of the sample is above 7. The precipitation may be mainly resulting from the reaction between the hypothetically existing $H^+$, $Na^+$, $Fe^{2+}$, $Fe^{3+}$, $Si^{4+}$, $Al^{3+}$ cations, and the $OH^-$, $Cl^-$, $O^{2-}$, $SO^{4-}$ anions, forming insoluble salts, which can be determined if X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) are conducted on the soil samples.

Other than precipitation, another possible mechanism of soil strengthening is the production of cementitious material, that is calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). This process requires high alkaline condition (more than 10).

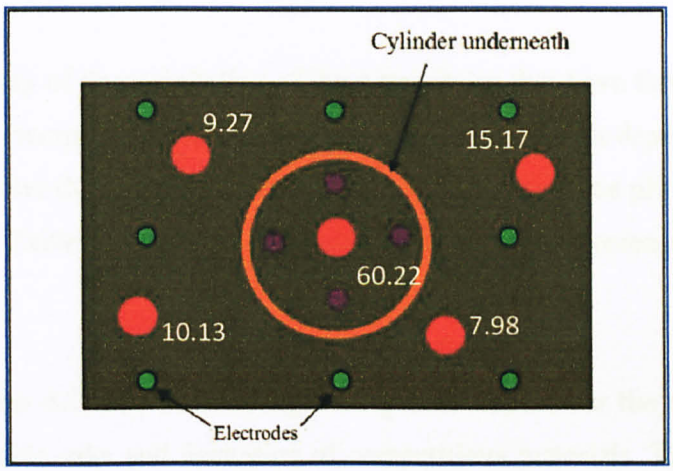
## 4.2 VANE SHEAR TEST

**Table 4: The result of vane shear test of control and treated sample**

| Sample | Shear Strength (kPa) | | |
|---|---|---|---|
| | Treatment (Single Polarity) | Treatment (Polarity Reversal) | Control |
| 1 | 13.71 | 9.27 | |
| 2 | 21.25 | 60.22 | |
| 3 | 7.55 | 15.17 | 6.04 |
| 4 | 18.85 | 7.98 | |
| 5 | - | 10.13 | |




**(a)**




**(b)**

**Figure 23: The shear strengths of the samples (a) Treatment with single polarity (b) Treatment with polarity reversal**

The result of vane shear test is shown by Table 4 and Figure 23. For both treatments, the highest shear strength is obtained in Sample 2.

In treatment with single polarity, the shear strength is increased as much as 350% compared to the control, and the lowest is, predictably, from Sample 3. Whereas, in control sample, the shear strength is 6.04 kPa, which is mainly contributed by the 7-day consolidation period. Interestingly enough, the shear strength of Sample 3, which was taken from outside of the perimeter of electrochemical treatment is improved by as much as 125%. This alone shows that the treatment, to a small degree, improves the strength of soil in the close proximity to the treatment boundary

In treatment with reversed polarity, increase is 900% over the control sample. Samples 1 and 4, which are taken from similar location orientation, show the lowest shear strengths. Generally, samples (other than sample 2) from treatment with single polarity show higher shear strength than treatment with polarity reversal. At the end of the first week of treatment phase, both of the treatments might be showing shear strengths of same range of values. However, after the reversal of the electrode configuration, the increase of strength slowed down, if not halted altogether. This is caused by the migration of ions towards their respective electrodes. This is also proven by the pH values, which is going to be explained in section 4.4.

However, the possibility of deprecipitation of the precipitates that have formed during the first 7 days is not ruled out. Precipitates that form when the pH is high might deprecipitate when the pH of the locality drops after the polarity of the electrodes is reversed. The pH values of the samples can be observed from Table 6 and Figure 25. This directly causes a decrease of the shear strength values.

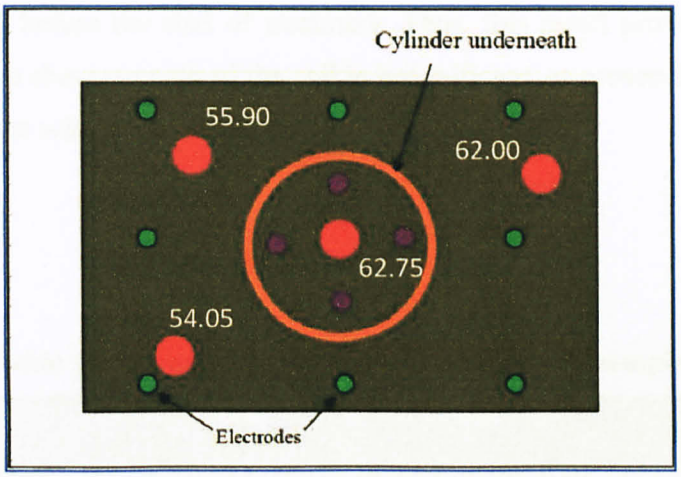
As discussed in section 4.1, the main strengthening mechanisms for the shear strength are the precipitation of insoluble salts and formation of cementitious materials. This hypothesis will be able to be clarified should XRD and XRF tests are conducted on the samples.

## 4.3 MOISTURE CONTENT

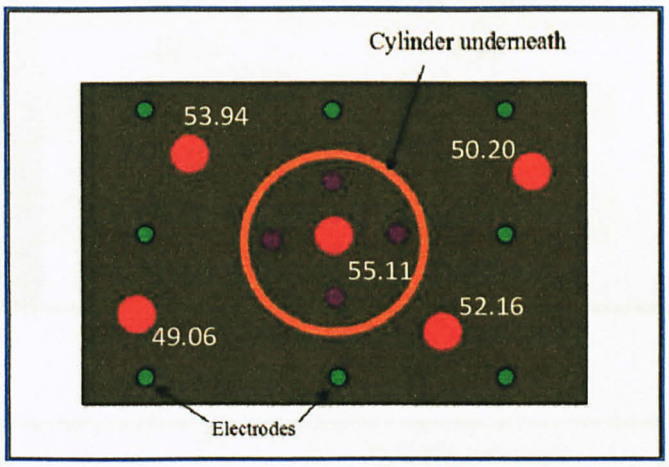
**Table 5: Moisture content of control and treated sample**

| Sample | Moisture Content (%) | | |
|---|---|---|---|
| | Treatment (Single Polarity) | Treatment (Polarity Reversal) | Control |
| 1 | 55.90 | 53.94 | |
| 2 | 62.75 | 55.11 | |
| 3 | 62.00 | 50.20 | 51.8 |
| 4 | 54.05 | 52.16 | |
| 5 | - | 49.06 | |

Table 5 and Figure 24 show the moisture contents of the Sample 1 to 5 for both treatment and for control. In the treatment with single polarity, the highest moisture content is observed from Sample 2 of both treatments, which is extruded from the area within the pile cylinder. This is due to the electro-osmotic effect of the treatment as water generally moves from anode to cathode.




**(a)**




**(b)**

**Figure 24: Moisture content of the samples (a) Treatment with single polarity (b) Treatment with polarity reversal**

Having said that, in electrochemical treatment such as this, the reduction of water is not the main mechanism in strengthening of the soil such as what is focused in electro-osmotic treatment. In electrochemical process, as discussed in section 2.2, the main strengthening mechanisms are precipitation to form insoluble salts, formation of cementitious materials, and flocculation of clay particles.

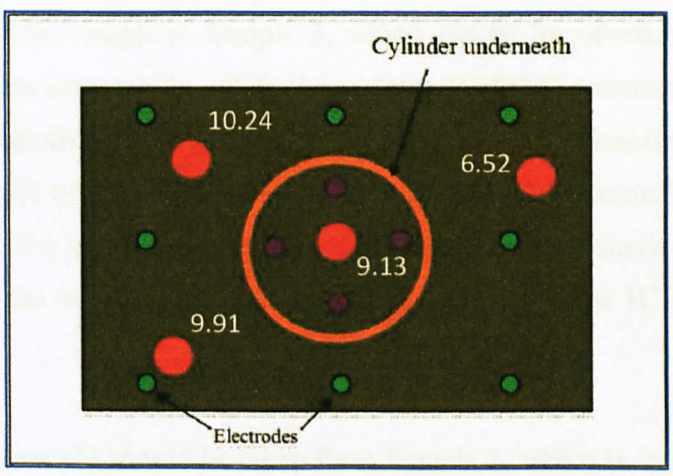
As a matter of fact, the highest shear strength is obtained at Sample 2, where the highest percentage of moisture content is observed. Not only that, the moisture content is even higher

than the original 55% before the start of treatment. Thus, this result proves that the effects of moisture content on the shear strength of the soil is insignificant, as proven by Syed (2007) in his electrochemical box test with 125 mm spacing.

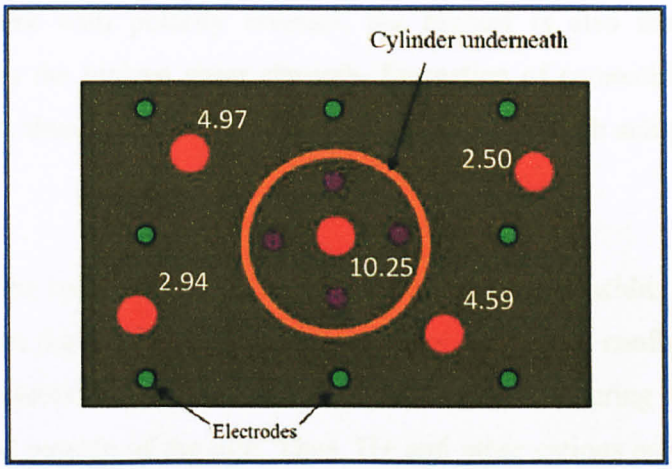
## 4.4 pH VALUES

**Table 6: pH values of the control and treated sample**

| Sample | pH | | |
|---|---|---|---|
| | Treatment (Single Polarity) | Treatment (Polarity Reversal) | Control |
| 1 | 10.24 | 4.97 | |
| 2 | 9.13 | 10.25 | |
| 3 | 6.52 | 2.50 | 3.91 |
| 4 | 9.91 | 4.59 | |
| 5 | - | 2.94 | |




**(a)**




**(b)**

**Figure 25: pH of the samples (a) Treatment with single polarity (b) Treatment with polarity reversal**

In treatment with single polarity, all four pH values of treated sample are basic, save for one, whilst the pH of control sample is acidic. The highest of the four samples of treated soil is Sample 1, which is taken from the vicinity of an anode. The second highest pH comes from Sample 2, followed by Sample 4.

However, the only acidic sample is Sample 3, which can be hypothesized by stating that the electrokinetics treatment occurs only within the perimeters of the connected electrodes. As such, this sample is representative of the soil area outside of the electrokinetic treatment boundary. Having said that, the pH of sample 3 still is higher than that of the control. This is because to a lesser degree, ions in the outside perimeter travel into the electrokinetic boundary due to the attraction induced by the voltage gradient. This mainly applies to the $H^+$ ions that are attracted towards the cathodes.

Theoretically, the highest pH should be taken from Sample 2, which is sampled from within the cylinder. As the principle reaction at the cathodes is the reduction of hydrogen from water (Potter, 1956), the concentration of hydroxide ions in the vicinity is increased, which in turn enhances the precipitation of hydroxide ions. This precipitation will result in higher pH.

While in the treatment with polarity reversal, the highest is also from Sample 2, which correspondingly shows the highest shear strength. Formation of cementitious materials is very rapid when pH is high, thus explaining why the highest shear strength and pH are taken from the same sample.

As can be seen from the result, samples 1, 3, 4 and 5 are generally acidic. This is caused by the H+ ions travelling from the anode to cathode. Note that the electrode configuration is reversed in the second week of electrokinetics treatment (Figure 20). Thus during the second week, the cathode will be placed outside of the pile. Thus, H+ and other cations are attracted towards the outward direction. This in turn lowers the pH values of the locality.

In explaining the result of sampled pH, the author hypothesizes that the pH have been higher at some points throughout the treatment phase and dropped at the end of it. This might have occurred when the $OH^-$ ions decreased when they chemically react to produce non-basic compounds. Thus, when the concentration of the $OH^-$ ions was optimum, the pH was at its highest and after being exhausted for the chemical reactions, the pH decreased slightly. The validity of this hypothesis can be clarified when the result of XDR and XRF results are obtained.

Thus, this hypothesis is backing up the possibility of formation of cementitious materials as one of the main mechanisms in the soil strengthening, which requires pH condition higher than 10.

## 4.5 OTHER OBSERVATIONS

### 4.5.1 Coloration

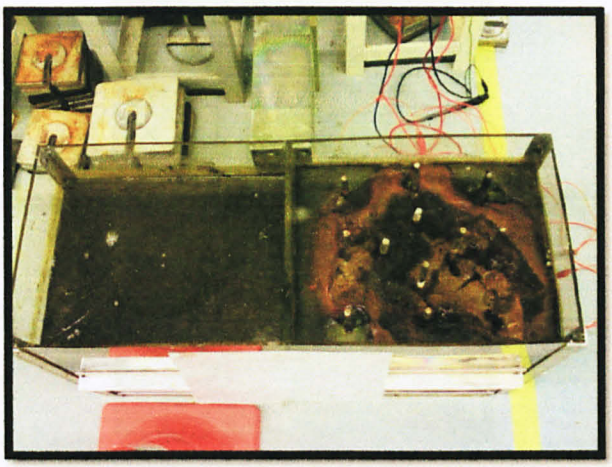


**Figure 26: Plan view of the control sample (left) and treated sample with single polarity (right)**

From the plan view of the treated sample, an observation is noted on a reddish brown ring generally in such a fashion as to connect the anodes (Figure 26). This is possibly caused by the formation of iron (III) compounds from the reaction between iron (III) ions from the steel electrodes and the hydroxide ions that traveled from the cathodes, chloride ions from the NaCl solution, and ions in the soil sample.

### 4.5.2 Observations on Electrodes

The anodes were severely corroded during the treatment of the marine soil (Figure 27). This strengthens the hypothesis that the ferrous (II) and ferrous (III) ions chemically reacting to other existing ions in the treatment box. The cathodes were not corroded.

Some of the anodes show greenish and pinkish red hues. This is possibly the physical appearance of the formation of ferrous (II) hydroxide, which is white in nature by is imparted with greenish

tinge with the presence of oxygen, and ferrous (III) compounds, which color range includes pinkish red.

**Figure 27: Corrosion of anode**

From both of these observations, it is clear that the electrodes are contributing to the concentration of ions for electrochemical reactions, and consequently, the strengthening of the marine clay sample.

### 4.5.3 Formation of Neutral Zone

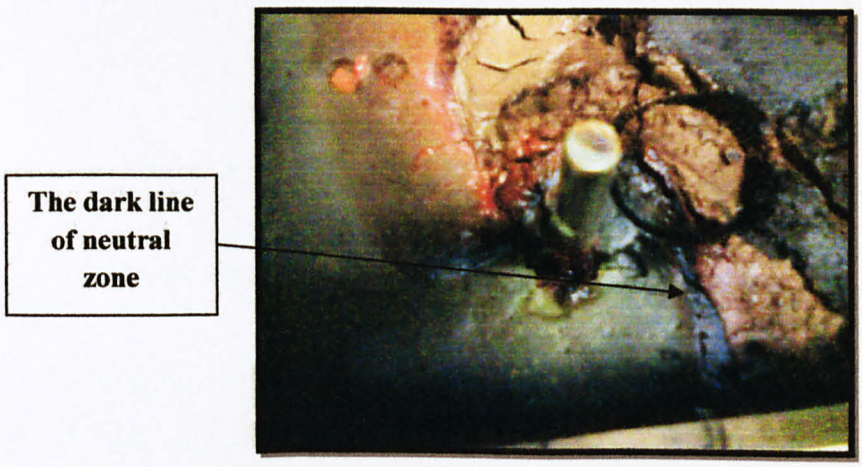



**Figure 28: Black curvy line showing the formation of neutral zone**

As shown in Figure 28, the neutral zone or neutral boundary is formed very close to the anode. The author hypothesize that the neutral zone if formed by precipitation when the acid front from anode and basic front from cathode collides and undergoes

Other observations noted from the treatment are the emission of heat and the decrease of voltage at the end of the treatment.

# CHAPTER 5
# CONCLUSION AND RECOMMENDATIONS

## 5.1 CONCLUSION

From the comparison of result, analysis and hypotheses for control and electrochemically treated marine soil sample, several conclusions can be drawn.

However, it is imperative to state that as the experiment was conducted in laboratory and controlled environment, this study serves as an approximate representation of the expected behavior in field condition, upon which preliminary assumption can be made.

The main conclusion of this study is that the shear strength and pullout capacity of the marine clay is increased after the electrochemical stabilization is conducted, which incidentally improves the pullout capacity of the pile in the sample.

Other conclusions drawn are:

i. The main strengthening mechanisms are the precipitation of ions to form insoluble salts and formation of cementitious materials, i.e. calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH).
ii. The moisture content of the locality is not representative of its strength. This is shown by the treated sample where the shear strength is highest when the moisture content is relatively high.
iii. The steel electrodes contribute to the increase of concentration of ions in the treatment box, which in turn increases the strengthening of the marine clay.

## 5.2 RECOMMENDATIONS

In order to further understand the mechanisms and effects of electrochemical stabilization on the marine clay and the improvement of its pile capacity, another treatment is conducted. In this treatment, the methodology will be similar to the conducted treatment, but the treatment phase is

shortened to just 7. After the end of the treatment, pull-out test and vane shear test will be conducted, as well as the pH and moisture content observed. The findings and data analysis will be presented in the final dissertation. The objective of this particular treatment is to observe the properties of the sample so that a better understanding is obtained for the analysis of the treatment with polarity reversal. With these data, clearer discussion can be deduced in what is happening in the sample during treatment.

For more study, several other parameters can be manipulated, such as the addition of varying types of electrolytes, type of electrodes, type of cylinder, and the variation of concentration of electrolytes.

Perhaps, during the study, other properties can be observed, such as the conductivity, continuous variation of voltage and current, pH across the sample, and longer time of treatment. This will provide more insight into the effects of this variation in parameters in the improvement of pile capacity in marine soil.

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APPENDIX 1

# APPENDIX 1

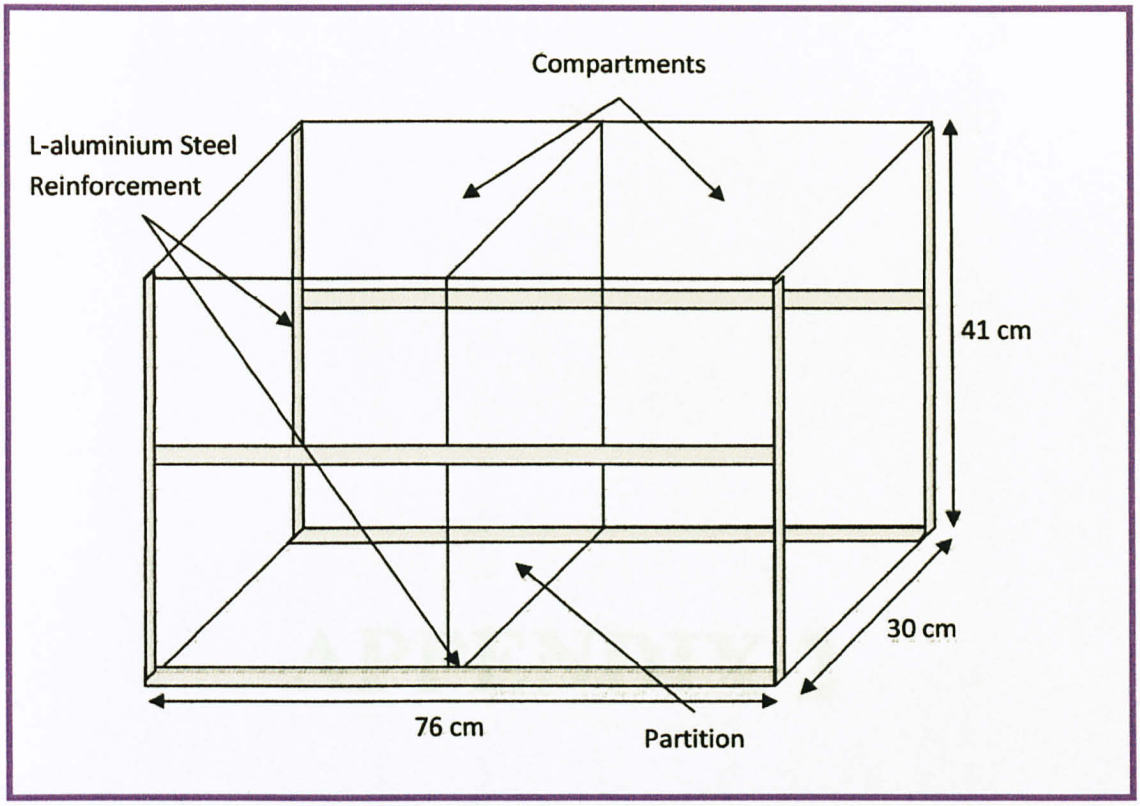



**Figure A1: Schematic diagram of the treatment box**

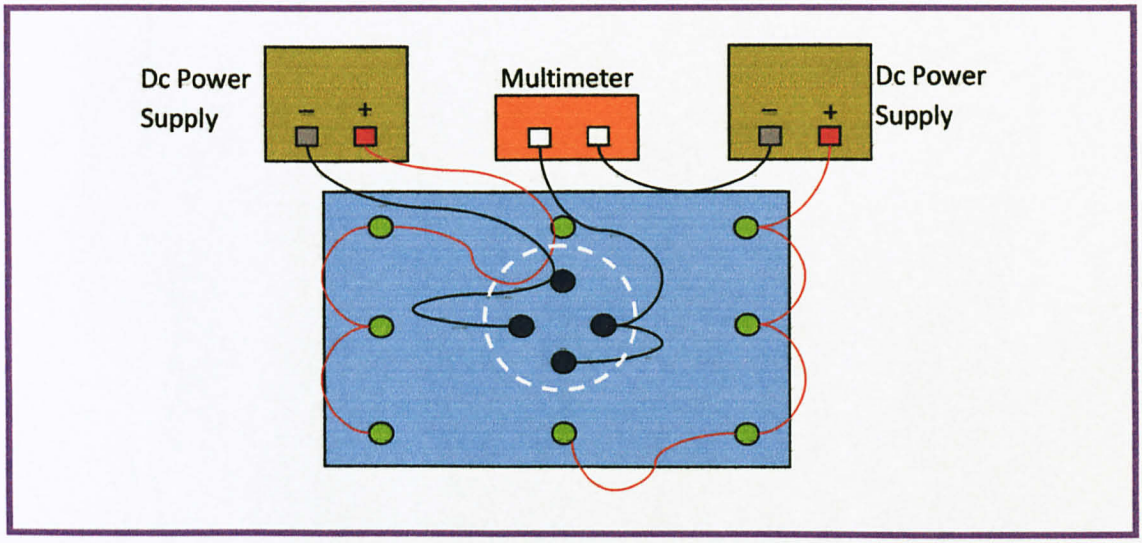



**Figure A2: Schematic diagram of the electrode wiring**

# APPENDIX 2

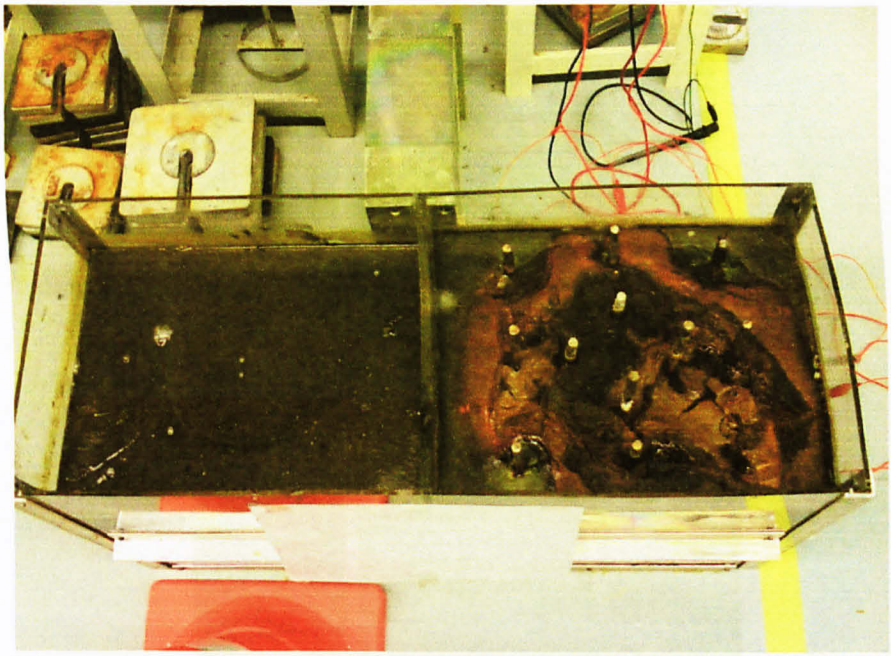


**Figure A3: Plan view of the control sample (left compartment) and treated soil with single polarity (right compartment)**

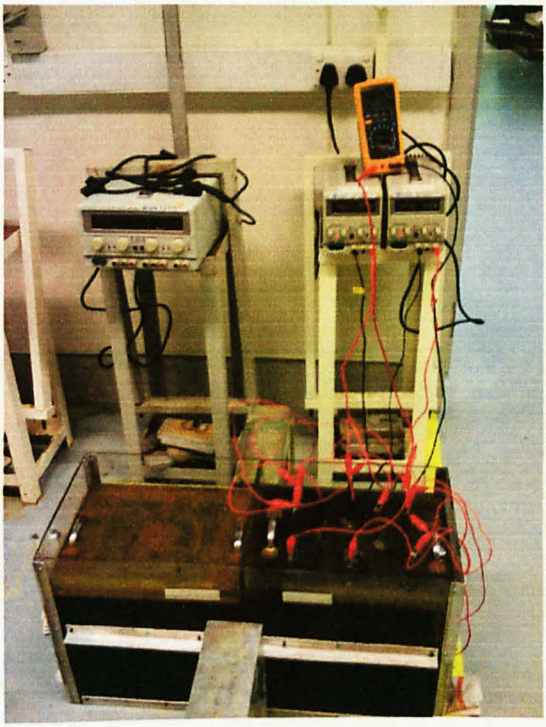


**Figure A4: Setup of treatment phase**

**Figure A5: Electrodes after the treatment phase**

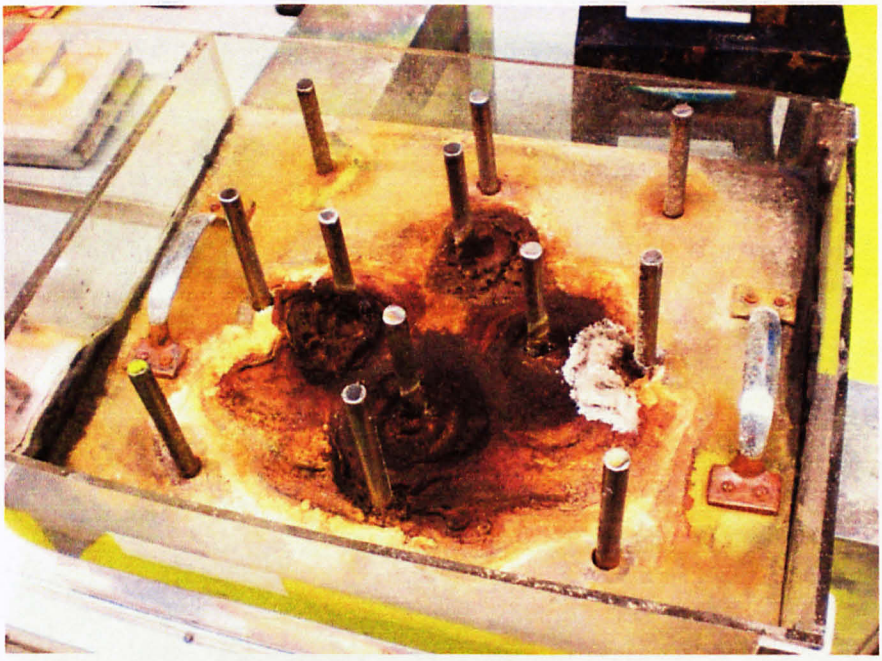


**Figure A6: The precipitation that is formed on top of the cover**

**Figure A7: Treatment with polarity reversal - needle-like precipitation by one of the electrodes. XRD and XRF test will be able to determine what chemical compounds the precipitation is formed of**

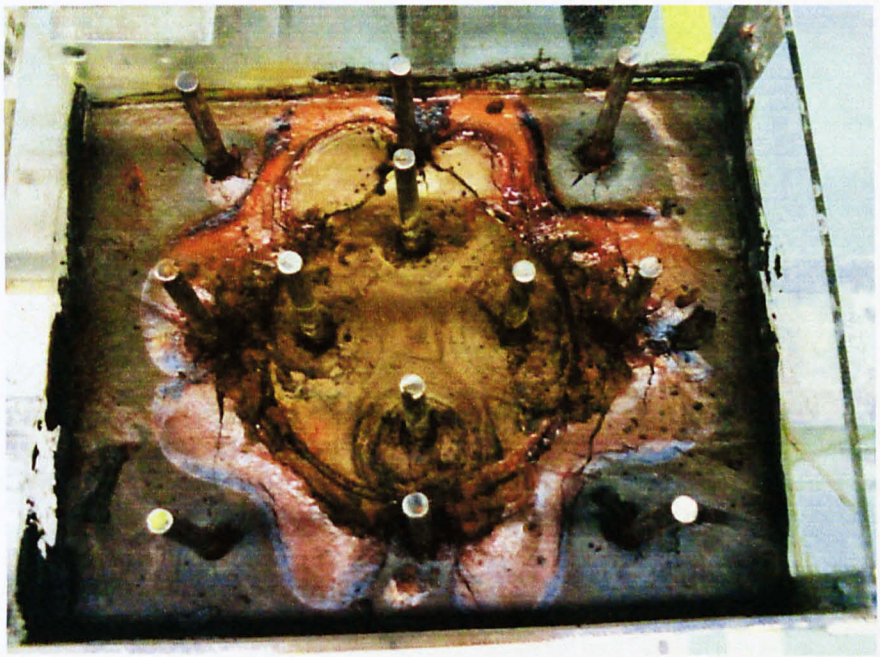


**Figure A8: Treatment with double polarity. Coloration is observed throughout the soil sample.**

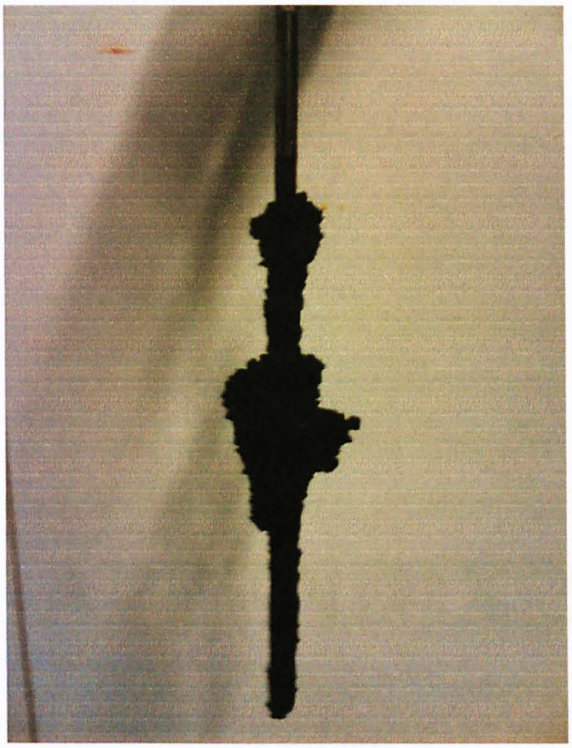


**Figure A9: Soil clinging to the electrode**

# APPENDIX 3

# One Dimensional Consolidation Properties
## (Oedometer)

ELE International

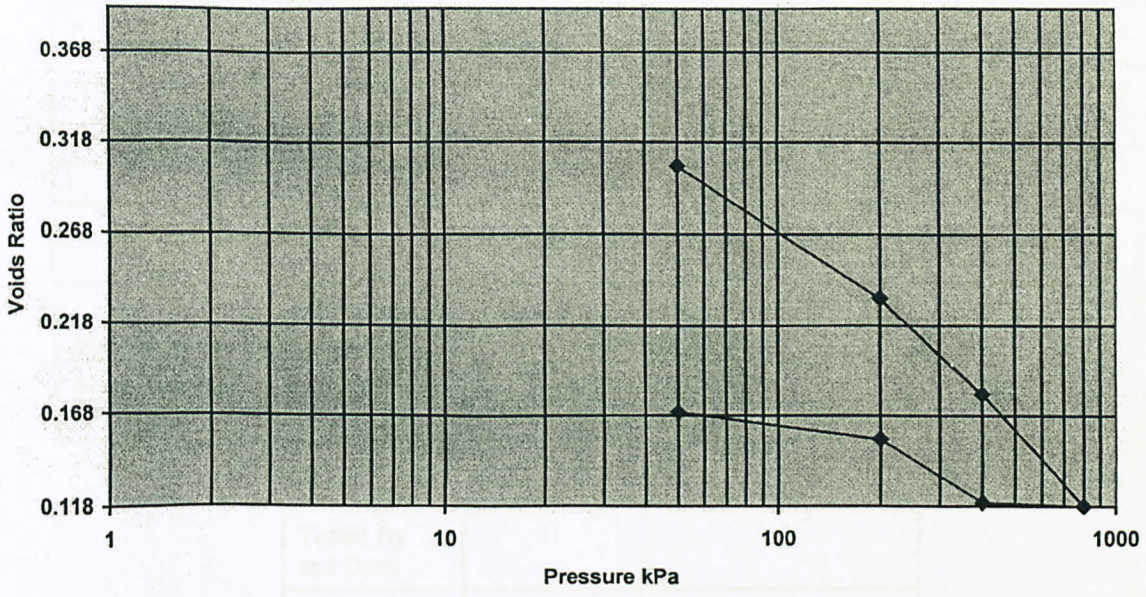
| | | | |
|---|---|---|---|
| **Client** | Ahmad Azimi Bin Kamaluddin | **Ref** | |
| **Project** | | **Job** | 2 |
| **Borehole** | | **Sample** | 2 |

| Test Details | | | |
|---|---|---|---|
| **Standard** | BS 1377: Part 5 : 1990 Clause 3 | **Particle Density** | 2.65 Mg/m3 |
| **Sample Type** | | **Variations from procedure** | |

| Specimen Details | | | |
|---|---|---|---|
| **Specimen Reference** | B | **Description** | |
| **Depth within Sample** | 0.00mm | **Orientation within Sample** | |
| **Sample Mass** | 72.10 g | | |
| **Preparation** | | | |
| **Comments** | | | |
| **Specimen Height** | 19.65 mm | | |

| Test Apparatus | | | |
|---|---|---|---|
| **Ring Number** | 2 | **Ring Diameter** | 49.53 mm |
| **Ring Height** | 19.65 mm | **Ring Weight** | 66.90 g |
| **Lever Ratio** | 10.00 : 1 | | |

**Voids Ratio Vs Applied Pressure**




| | | | |
|---|---|---|---|
| **Height of Solid Particles** | 14.12 mm | **Swelling Pressure** | 0.0 kPa |

# One Dimensional Consolidation Properties
## (Oedometer)

ELE International

| | | | |
|---|---|---|---|
| Client | Ahmad Azimi Bin Kamaluddin | Ref | |
| Project | | Job | 2 |
| Borehole | | Sample | 2 |

| | | | |
|---|---|---|---|
| Initial Moisture Content | 0.00 % | Final Moisture Content | 4.75 % |
| Initial Bulk Density | 1.90 Mg/m3 | Final Bulk Density | 14.89 Mg/m3 |
| Initial Dry Density | 1.90 Mg/m3 | Final Dry Density | 14.21 Mg/m3 |
| Initial Void Ratio | 0.3916 | Final Void Ratio | -0.8136 |
| Initial Degree of Saturation | 0.00% | Final Degree of Saturation | -15.48 % |

| Pressure (Loading Stages) | Coefficient of Volume Compressibility ($m_v$) | Coefficient of Consolidation ($c_v$) |
|---|---|---|
| 0.00 | | |
| 50.0 kPa | 1.24m2/MN | Inf m2/Year |
| 200.0 kPa | 0.37m2/MN | Inf m2/Year |
| 400.0 kPa | 0.22m2/MN | Inf m2/Year |
| 800.0 kPa | 0.13m2/MN | Inf m2/Year |
| | | |
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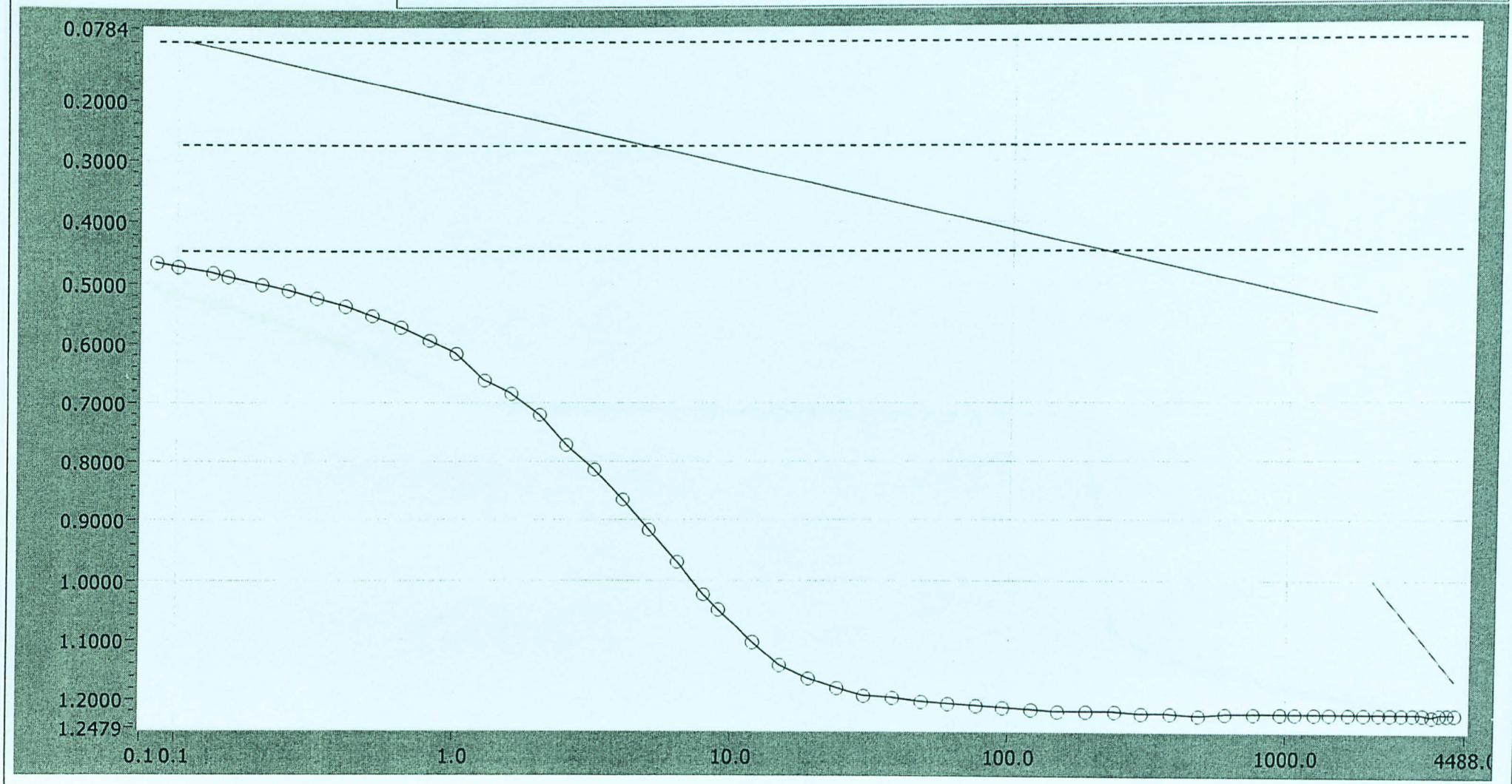
| | |
|---|---|
| Method of Time Fitting Used | Root Time |
| Mean Laboratory Temperature | 23.0 deg.C |
| | |

| | |
|---|---|
| Tested By and Date: | |
| Checked By and Date: | |
| Approved By and Date: | |

# Loading Stage 1 of 4

| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |

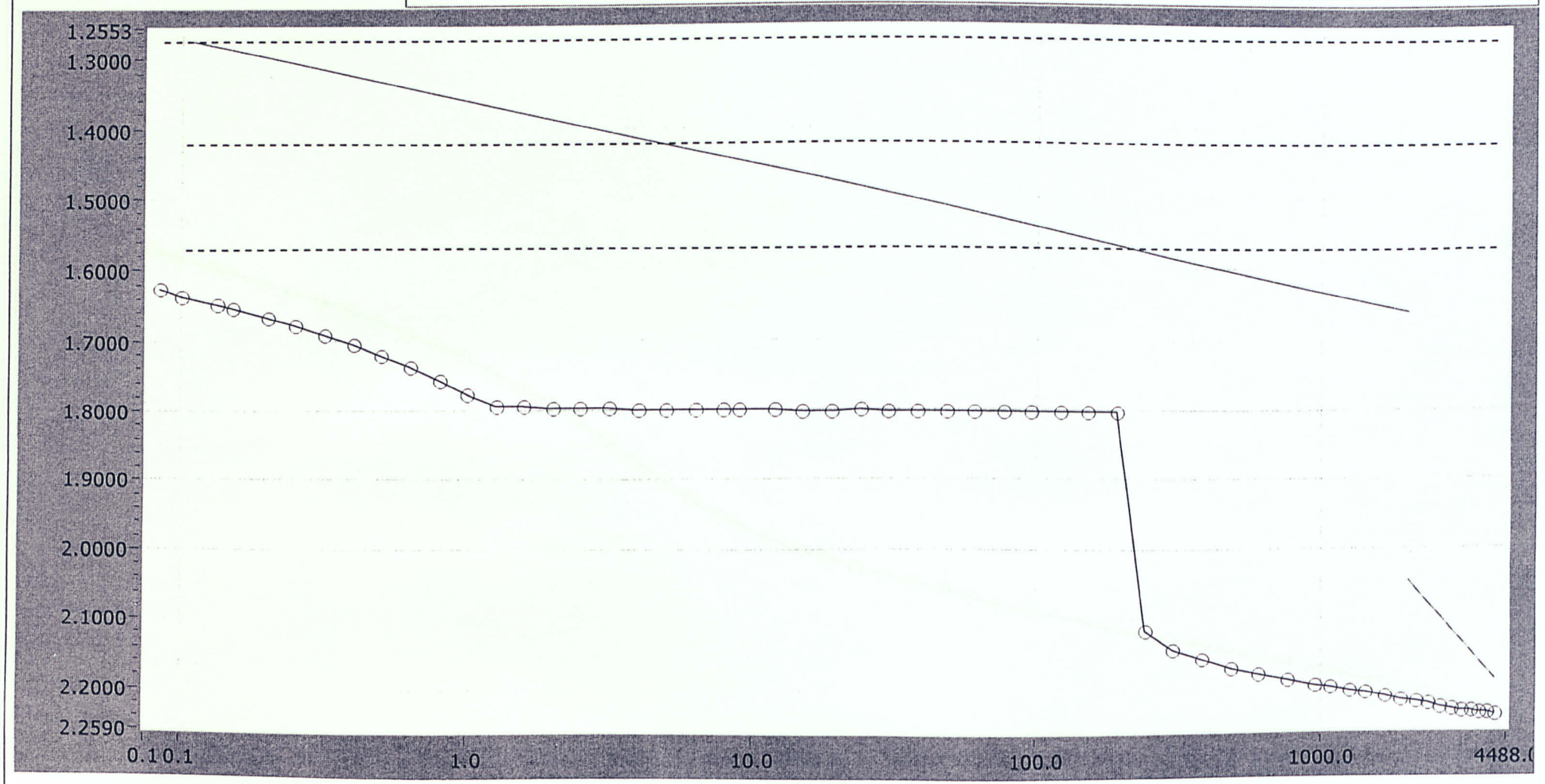
Compression Gauge mm




**DS7 - Geotechnical Software**

# Loading Stage 2 of 4

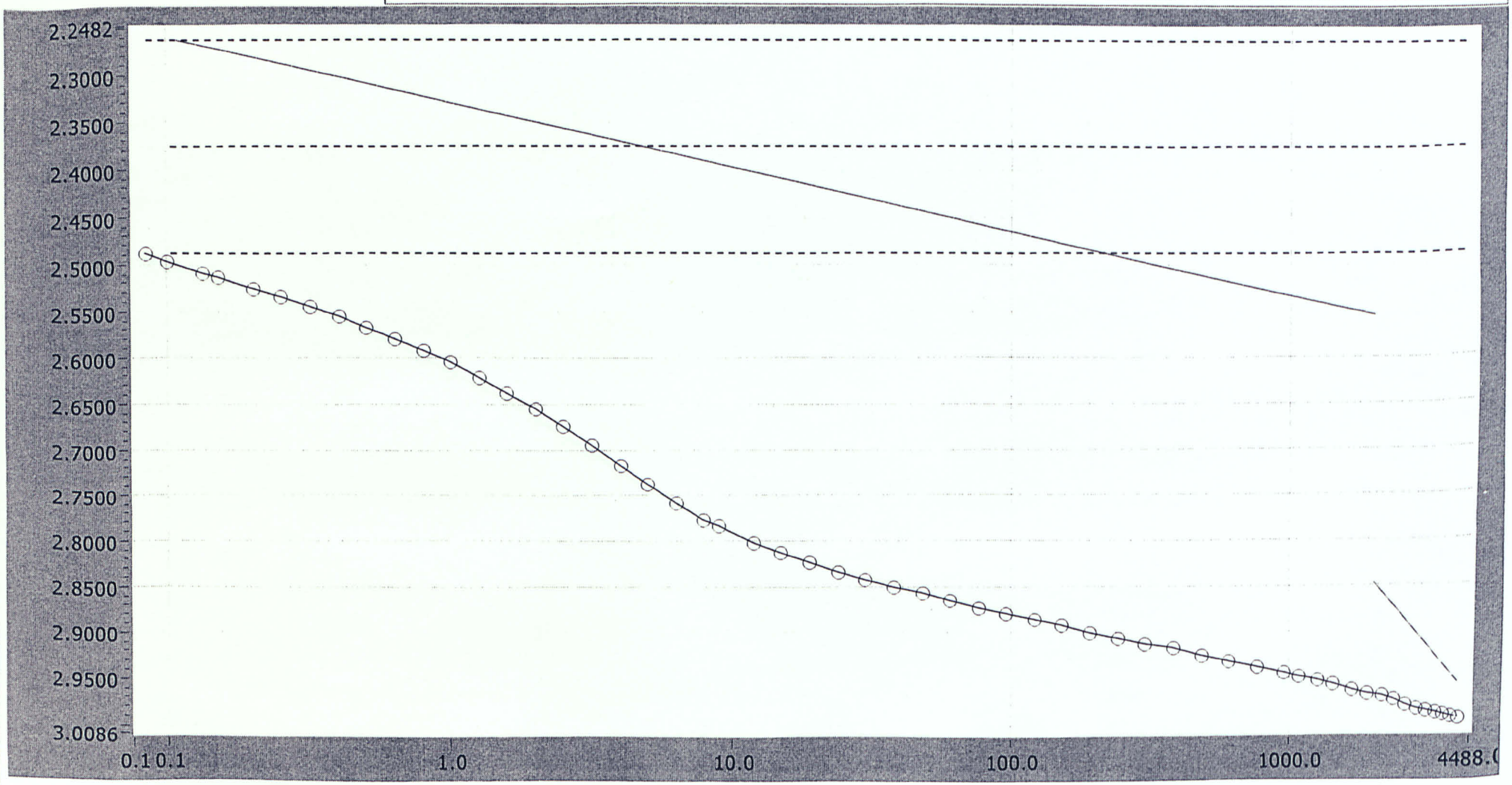
| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |



# Loading Stage 3 of 4

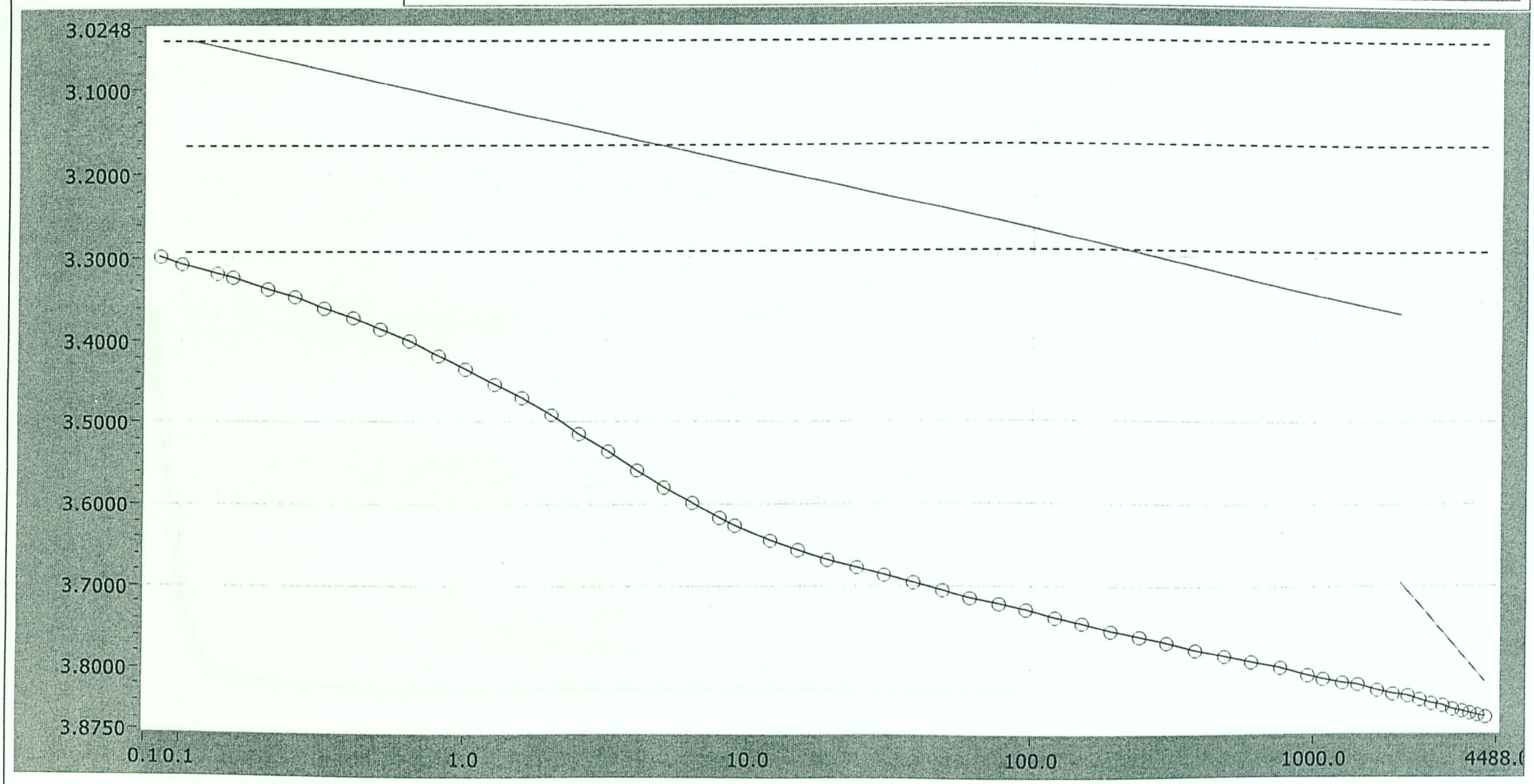
| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |

Compression Gauge mm



# Loading Stage 4 of 4

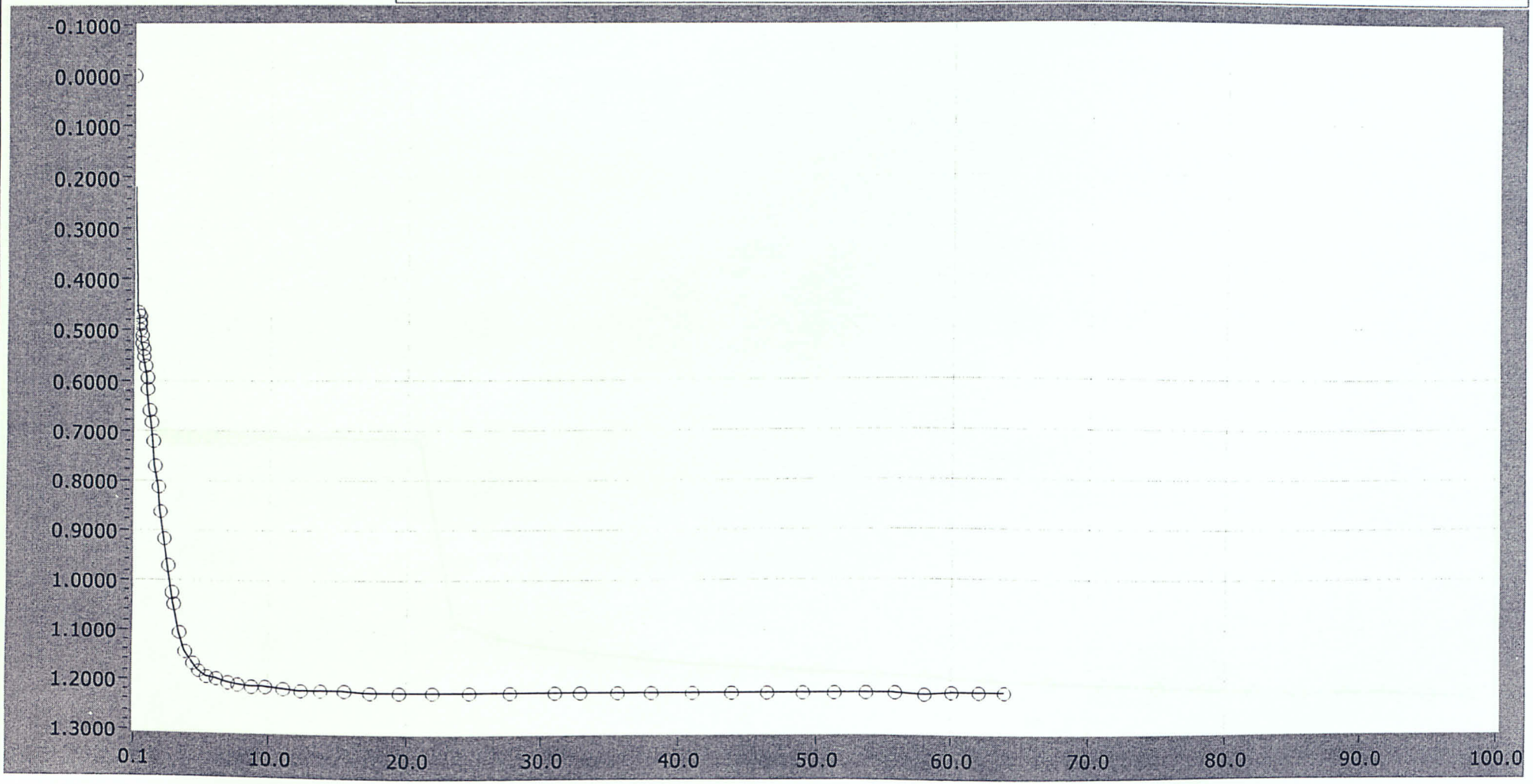
| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |



# Loading Stage 1 of 4

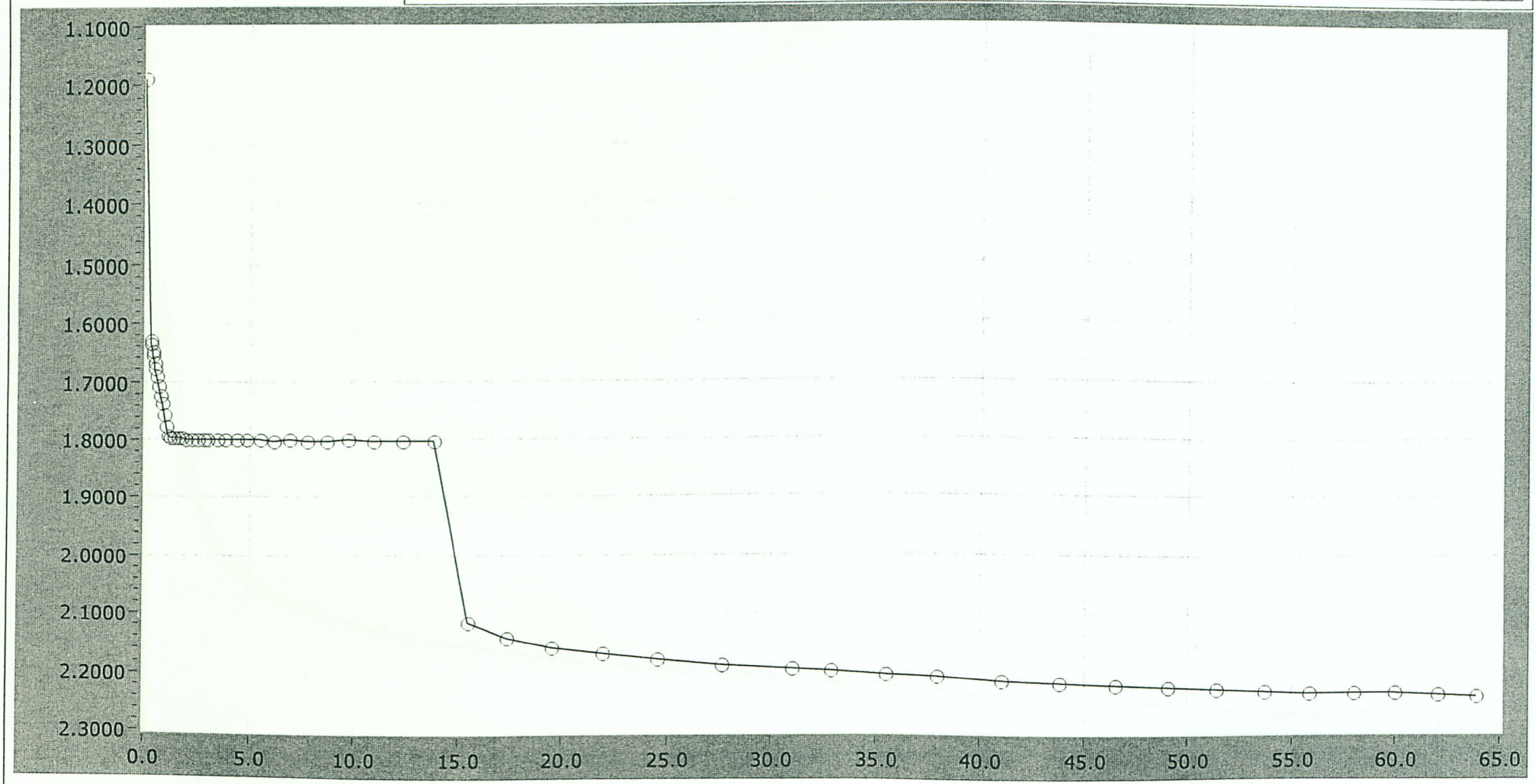
| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |

Compression Gauge mm



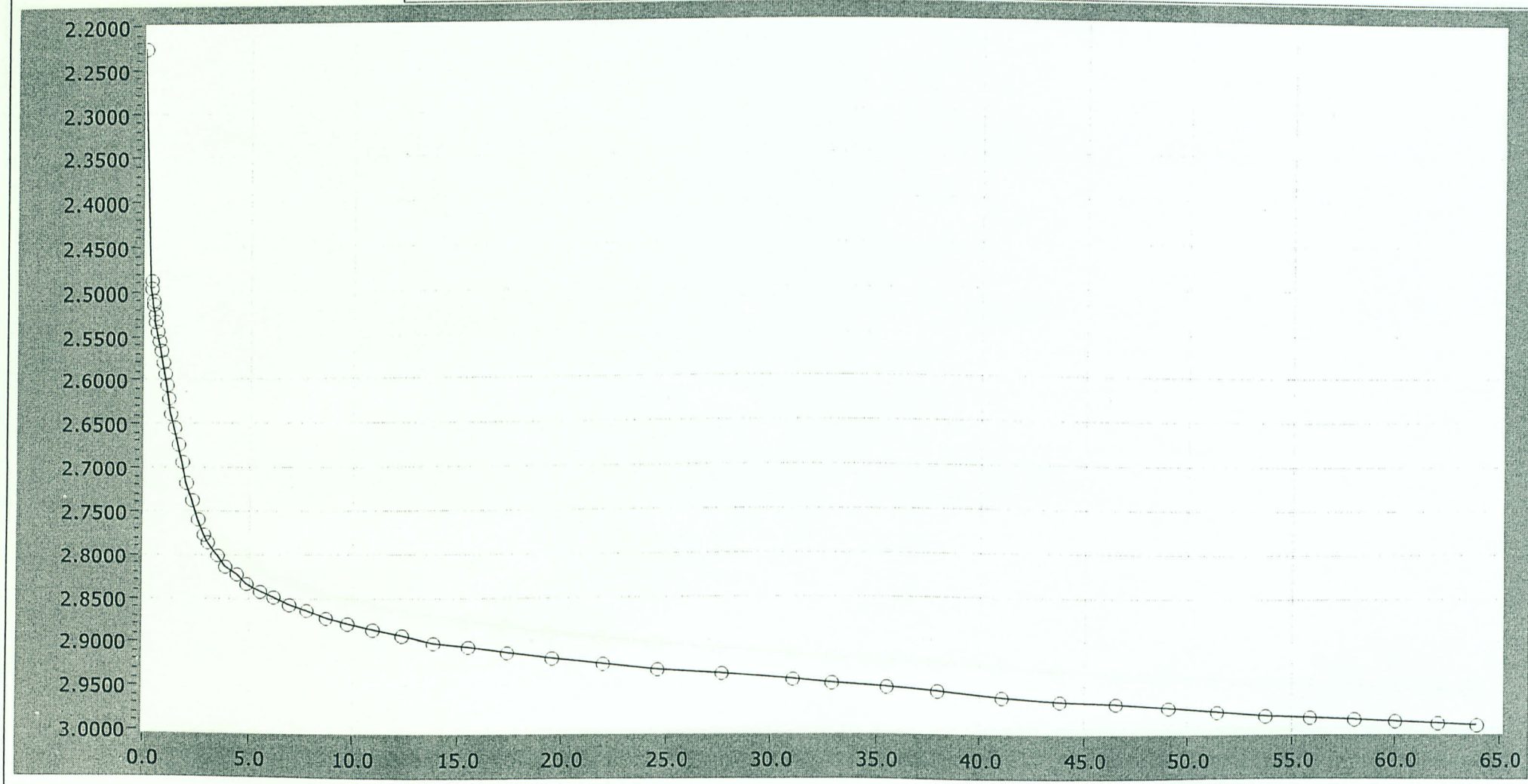
# Loading Stage 2 of 4

| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |



# Loading Stage 3 of 4

| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |



# Loading Stage 4 of 4

| Client | Job Number | Sample Number |
| --- | --- | --- |
| Ahmad Azimi Bin Kamaluddin | 2 | 2 |